THE VULNERABILITY OF NEW ZEALAND LIFELINES INFRASTRUCTURE TO ASHFALL

A thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy in Hazard and Disaster Management in the University of Canterbury

by

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ABSTRACT

Risks posed by geohazards to urban centres are constantly increasing, due to the continuous increase in population and associated infrastructure. A major risk to North Island urban centres is impacts from volcanic ashfall. This study analyses the vulnerabilities of selected New Zealand lifelines infrastructure to volcanic ash, to better understand and mitigate these risks. Telecommunications and wastewater networks are assessed, as is the vulnerability of Auckland Airport and grounded aircraft. The ability of vehicles to drive on ash covered roads is also tested, to determine the extent to which emergency services, utility providers and the public will be able to travel during and immediately after ashfall. Finally, air-conditioners have been identified as a significant vulnerability during ashfall, due to the high dependence on cooling for infrastructure and lifelines providers. These are examined to quantify the effects of ashfall on their performance.

Each of the selected infrastructure types is assessed through a review of past impacts of ashfall, and experimentation either in the field or under laboratory conditions. Where appropriate, mitigation options that reduce identified vulnerabilities are considered. In most cases these options are operational rather than physical engineering solutions, and indicate pre-planning and response requirements.

Key recommended mitigation options include the acquirement or strategic relocation of resources prior to ashfall, regular cleaning and maintenance of essential air conditioners during ashfall to enable their continued use, access to appropriate vehicles for utility providers to reach infrastructure, and discharge of untreated wastewater into Waitemata harbour at Orakei during ashfall on Auckland, to preserve the ability to continue treating wastewater at the Mangere treatment plant.

GLOSSARY OF TERMS AND ACRONYMS

Airside	The area of an airport beyond the terminals used by aircraft for loading, unloading, takeoffs and landings
AVF	Auckland Volcanic Field
DAC	Dirección de la Aviación Civil: The Ecuadorian civil aviation Authority
EMAAP	Quito Water Supply Agency (Ecuador)
ENAC:	Ente Nazionale per l'Aviazione Civile: The Italian national civil aviation authority.
FEMA	Federal Emergency Management Agency (USA).
GNS Science	Geological and Nuclear Sciences (New Zealand)
IGEPN	Instituto Geofisico, Escuela Politecnica Nacional (Ecuador):The institute of geophysics, national polytechnic school
INGV	Istituto Nazionale di Geofisica e Vulcanologia: The Italian national institute of geophysics and volcanology
NAS	Naval air station
NIWA	National Institute of Water and Atmospheric Research (New Zealand)
NOTAM	Notice to Airmen
NVO	Nucleo di valutazione operative. Nucleus of operative assessment: The crisis team at Fontanarossa airport.
PAHO	Pan American Health Organisation
Pitot tubes	Instruments of the outside of an aircraft cockpit that measure airspeed
SAC	Società Aeroporto Catania. The company that operates Fontanarossa airport
SIGMET	Significant Meteorological Information, a meteorological advisory containing information about the safety of all aircraft
SMEC	Snowy Mountains Engineering Corporation
Tephra	Ash and lapilli. Ash grainsize is < 2mm, lapilli is 2 – 64 mm. Tephra refers to both. In this work the terms ash and tephra are usually used interchangeably
TVZ	Taupo Volcanic Zone
USGS	United States Geological Survey
VAAC	Volcanic ash advisory centre
VAAS	Volcanic ash advisory system (NZ)

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APPENDIX 5 Leonard, G. S., Johnston, D. M., Williams, S., Cole, J. W., Finnis, K., Barnard, S., (2005) Impacts and management of recent volcanic eruptions in Ecuador: lessons for New Zealand. *Institute of Geological & Nuclear Sciences science report* 2005, 20: 51. Included on attached CD ROM

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CHAPTER 1: INTRODUCTION

1.1 Background

Volcanic eruptions have the capacity to cause widespread damage and destruction. Communities throughout history have been subjected to the sometimes disruptive, sometimes catastrophic impacts of volcanism (Cashman & Giordano, 2008). This is in part because historically the fertile farmland associated with volcanoes has made them attractive places to live, despite the hazards (Annen & Wagner, 2003). Urbanisation in the last 250 years has led to increased global exposure to natural hazards, as concentrations of population and infrastructure in hazard zones have a greater potential for disasters than more dispersed rural communities (Chester et al., 2001). In terms of volcanism this has been evidenced particularly by the deaths in 1985 of >23,000 people in living in Armero, Colombia buried by lahars from Nevado de Ruiz (Voight, 1996). Losses due to volcanic activity in the 1990s included the devastation of two cities (Rabaul and Plymouth), the deaths of between 560 and 1,300 people, the displacement of more than 520,000 people and over one billion U.S. dollars in financial losses, (Annen & Wagner, 2003). In the last decade more eruptions have affected urban areas in several countries, perhaps most significantly the destruction of Chaiten town, Chile by the 2008 eruption of Chaiten Volcano (La Nacion, 2009).

Despite these recurring impacts, several towns and cities are located within kilometres of frequently erupting volcanoes, for example Kagoshima, Japan (>10 km from Sakurajima Volcano); Catania, Italy (centred 25 km from the summit of Etna); Quito, Ecuador (~ 10 km from the summit of Guagua Pichincha); Ambato, Ecuador (~30 km from Tungurahua). Many more are situated close to or on top of volcanoes that may not have erupted in recent history, but are still active; In New Zealand Auckland is a prime example of this, as is Rotorua. Immediate proximity to a volcano is not requisite to be threatened by volcanism; centres located hundreds of kilometres from volcanoes may be subject to impacts from volcanic ash.

Volcanic ash may travel vast distances; eruptions can have impacts on the other side of the world. Ash clouds from The 1991 Mt Hudson eruptions in Chile were identified over Australia (Barton et al., 1992), and ash likely to be from the 2002 Reventador eruption in Ecuador was encountered by aircraft over Micronesia (Tupper et al., 2006). Ash from the 1991 Pinatubo eruption circled the globe, traces were even found in Antarctica (Cole-Dai et al., 1997). Since ash may travel so far, most instances of ashfall impacting urban centres involve minor thicknesses of ash. Occurrences of more than a few millimetres of ashfall impacting urban areas are rare. Even those cities existing close to frequently erupting volcanoes have in most cases received only light ashfall, e.g. Kagoshima, Japan (Durand et al., 2001); Catania, Italy, (Barnard, 2004); Quito, Ecuador (Leonard et al., 2005). Each of these centres has experienced light ashfall (up to a few millimetres) on more than one occasion in the last decade. The few existing examples of heavier ashfall impacting urban areas are often accompanied by other volcanic hazards, such as lahars or pyroclastic flows. Examples include Rabaul township during the 1994 Rabaul eruption, (Blong & McKee, 1995) Plymouth during the 1995 (onwards) eruptions of Soufriere hills, (Young et al., 1998) and Chaiten township during the 2008-present day eruption of Chaiten Volcano (T. Wilson, pers. comm., 2009).

1.2 Context

The reliance of communities on lifeline utilities (lifelines) to maintain their economies, health, safety and quality of life is greater now than ever before. Electricity, water supplies, wastewater, communications and transportation networks are all essential to urban centres. Without the continued operation of these lifelines, urban life ceases to be sustainable. Continuity of lifelines operations during emergencies is essential to preserving quality of life. Maintaining these essential services not only benefits the community directly but in some cases may even negate the need for evacuations. The elevated community risk exposure to secondary hazards such as diseases, and water contamination through infrastructure failure may be the cause for such evacuations rather than the primary (volcanic) hazard realisation. In order to achieve continuity of lifelines, infrastructure providers need to develop effective risk management strategies to cope with foreseeable hazards. Holistic risk management relies on a cyclic process that encapsulates the identification, analysis and evaluation of any risks as risk assessment (figure 1.1). However, risk assessment is only one part of the process. Its role is to quantify the risk within the given context and to inform decision makers and stakeholders of the risk exposure profile so that appropriate treatments can be implemented. To be effective, the risk management process also requires continuous review as treatment, communication inputs and situational changes impact the level of risk tolerance and likelihood of risk realisation.

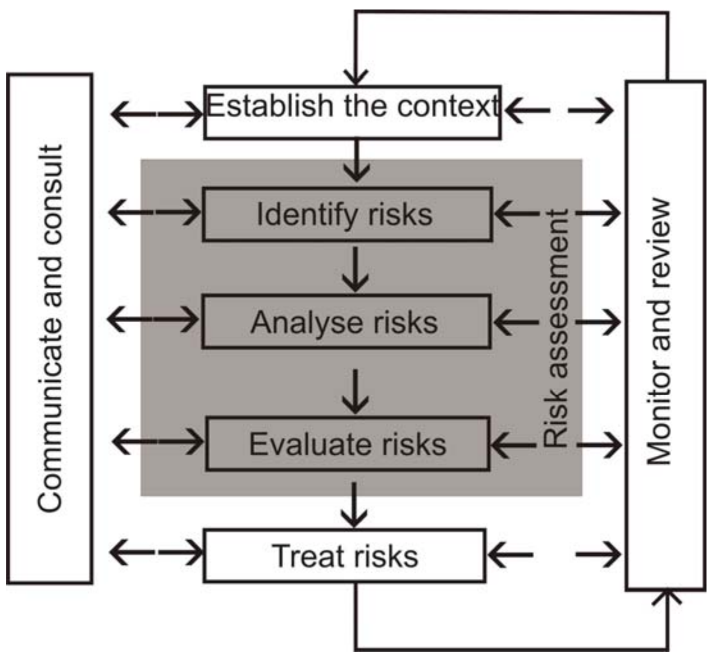

Figure 1.1 Generalised risk management process – Overview (after AS/NZS 4360:2004).

By living close to or on an active volcano we tacitly accept the risk posed by that volcano. The nature of the geological setting of New Zealand necessitates this in a large part of the North Island. Preventing eruptions is not possible, but exercising some control over the amount of risk they pose is, through effective hazard management.

The numerous natural hazards existing in New Zealand require extensive hazard management planning and legislation. Regional Civil Defence Emergency Management Groups, local authorities and emergency services are responsible for implementing local risk management and civil defence emergency management

(ODESC, 2007). Their responsibilities are set out in the Resource Management Act (RMA) (1991), the Civil Defence Emergency Management Act (CDEM) (2002), the Building Act (2004), and to some extent the Local Government Act (2002). The RMA requires territorial authorities and regional councils to avoid or mitigate natural hazards. The CDEM act specifies the responsibilities of government departments, lifeline utilities and emergency services in the context of the 4Rs of emergency management (reduction, readiness, response and recovery). It seeks to achieve acceptable levels of risk for communities, and required the formation of CDEM groups. These 16 regional groups seek to identify gaps in hazard knowledge and inefficiencies in mitigation (ODESC, 2007). Supporting these CDEM groups are other organisations such as the National Engineering Lifelines Committee (NELC), (whose members include EQC, MCDEM, NIWA, GNS Science and various lifelines providers) and various regional engineering lifelines groups, such as the Auckland Engineering lifelines group (AELG).

This multi-agency approach to emergency management illustrates the importance placed on hazard and emergency management in New Zealand. The legislative requirements to prepare for and mitigate against potential hazardous events necessitate a good knowledge not only of the hazards themselves, but the extent of the risk they pose. Effective management of any risk requires a quantitative estimate of the degree of that risk and the associated hazard. In terms of geohazards (including volcanism), risk is a function of hazard, exposure, vulnerability and probability. All of these aspects need to be defined to be able to quantify risk. The research in this thesis has focussed on the vulnerability aspect of this equation. Other applicable research into geohazards and risk is conducted both overseas and in New Zealand. Locally this is performed largely by crown research institutes (CRI's) such as NIWA and GNS, and by New Zealand's universities, often in conjunction with those CRI's. Current work includes the *Riskscape* and DEVORA (Determining Volcanic Risk in Auckland) projects. *Riskscape* is a "multi-hazard decision support tool", which in part offers identification of and quantification of risks and potential losses from different hazard events (NIWA 2008). The DEVORA research programme, a collaboration between GNS Science and Auckland University's Institute of Earth Science and Engineering, seeks to assess volcanic hazard and risk in Auckland. The research conducted for this thesis will feed not only into these projects but will be directly available to be used by the infrastructure providers concerned. In this way this thesis is adding to a greater body of extant and continuing work.

This thesis seeks to assess risks posed to lifelines infrastructure from volcanic ashfall, through a vulnerability analysis of selected infrastructure to volcanic ash. The analysis acts to identify which aspects of infrastructure are vulnerable, and analyses these vulnerabilities to determine potential consequences. This in turn will arm infrastructure providers with the necessary tools to fully evaluate the risks posed by volcanic ash to their respective networks. Recommended mitigation strategies are given where appropriate to facilitate this process. The application of this knowledge will increase the organisational resilience of lifelines providers, which will in turn increase the resilience of the community. Analyses of ashfall impacts are conducted on the following lifelines and infrastructural types:

- Telecommunications
- Air conditioning systems
- Aviation infrastructure and grounded aircraft
- Road transportation (vehicle mobility)
- Wastewater systems

Notable lifelines omitted from this research are electrical distribution networks and water supplies. This is because this work complements parallel streams of research by other researchers into lifelines vulnerability. Current research in New Zealand on how ash impacts electrical distribution networks is being conducted at both Massey University (by Ian Chapman) and at the University of Canterbury (by John Wardman). Water supply vulnerability to ashfall has recently been addressed through literature review and modelling (Stewart et al., 2006), and more specifically as a study on potential impacts of ashfall on water supplies in Auckland (Johnston et al., 2004). The infrastructure types selected for this research were chosen because they represent essential lifelines and services in New Zealand, about which there is insufficient knowledge to quantify risk. Assessing the vulnerability of these types of infrastructure to volcanic ash is a vital prerequisite for enabling risk management practices to be put into place by infrastructure providers and local or regional authorities. While this research focuses on the physical vulnerability of New Zealand infrastructure to volcanic ash, most results are applicable internationally, as much infrastructure is essentially the same worldwide.

1.3 Hazards caused by volcanic ash

Volcanic ash is hazardous for several reasons. It consists of very small fragments (<2 mm diameter) of volcanic rock and glass. Because of this small size it is difficult to prevent it getting into buildings, vehicles, and machinery. The hard nature of volcanic ash renders it extremely abrasive, whether it is from a mafic or more silicic source. As its small size makes it very penetrative, it can cause much damage by abrading moving parts on machinery. It is also respirable, creating a health hazard, potentially more so for asthmatics (Horwell & Baxter, 2006).

Ash is heavy, and it can be produced and deposited in large volumes. The weight of thick deposits of ash may exceed design loads of structures. Furthermore it may absorb up to 50% of it own volume in water, increasing its weight significantly. This can lead to building and/or roof collapse, something that has featured in many historical eruptions, e.g. Tarawera 1886 (Keam, 1988), Pinatubo 1991 (Casadevall et al., 1996), Rabaul 1994 (Blong & McKee, 1995). Roof collapse may occur with as little as ~15 cm of ash, damage may occur with even less. Figure 1.2 illustrates roof collapse in Rabaul, 1994.

Figure 1.2: Collapsed police barracks in Rabaul, 1994, after being covered by >600 mm of ash (Blong & McKee, 1995).

Additionally, large volumes of ash can create blockages and obstructions. The usual movement of air may be restricted as ash blocks air intakes and filters on machinery, vehicles and air handling units (e.g. air conditioners). Water movement is also restricted by blocked drains and sewers. This can lead to roofs leaking if ash clogs downpipes and spoutings. Flooding and/or sewage overflows from blocked up wastewater systems are another potential hazard caused by ashfall. Thick deposits (over a few centimetres) can block roads to traffic, especially on hilly areas.

Aerosols attached to freshly erupted grains of ash are potentially extremely acidic, creating corrosion risks to exposed metals. This affects machinery, vehicles and many rooftops. The same acidic properties can contaminate water supplies if reservoirs are above ground.

As well as the problems caused by abrasion, loading, blockages and corrosion, the slipperiness of small grains of volcanic ash constitutes a hazard in itself. This has in the past caused traffic accidents due to loss of traction (e.g. Barnard, 2004).

1.4 Volcanism in New Zealand

New Zealand's geographic location on the boundary of the Pacific and Australian plates makes it a very active place geologically. The North Island hosts several active volcanoes, most of which could potentially deposit ash over any parts of the North Island, or in rare cases even the South Island (figure 1.3).

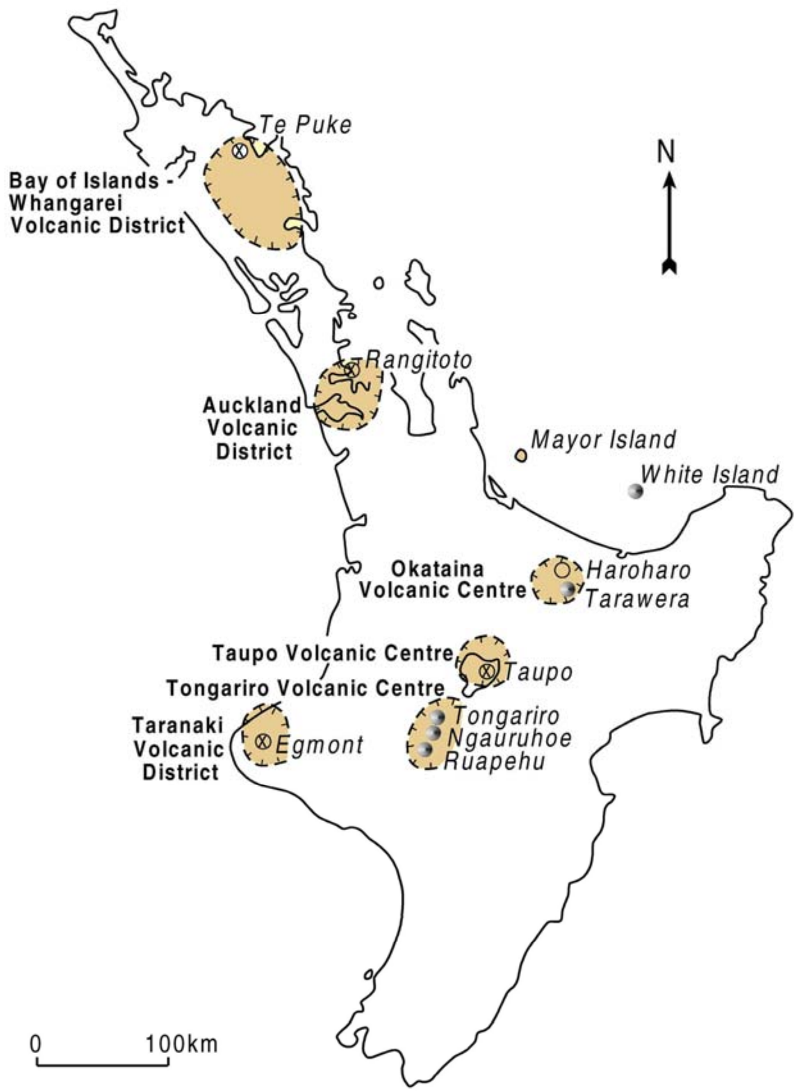

Figure 1.3: Volcanic centres of the North Island. The Grey circular icons indicate Volcanoes that have been active in the last 150 years (modified from Cole & Nairn, 1975)

The most frequent source of volcanic ash in the New Zealand over the last 150 years is the Tongariro Volcanic Centre (Cole & Nairn, 1975; Guffanti et al., 2008) Predominant wind directions in the North Island are from west to east, therefore the cities and towns of the eastern North Island have historically had the greatest risk realisation, experiencing ashfall from this source. However, the greatest damage potential from ashfall exists in New Zealand's largest city, Auckland. Auckland's risk is in part due to the potential economic consequences of ashfall on the city, but also because Auckland itself is situated on an active basaltic volcanic field (the Auckland Volcanic Field, or AVF). Moreover the active volcanic centres of the Taupo Volcanic Zone have all deposited ash on Auckland in the past (Sandiford et al., 2001). Auckland is also at risk from Taranaki Volcano; the probability of tephra-induced building damage occurring in Auckland from this volcano may be greater than from a local eruption, due to the higher probability of an eruption from Taranaki (Magill & Blong, 2005). Local eruptions in Auckland, while statistically less frequent have the capacity to cause far more damage. The Rangitoto eruption was not only the most recent, occurring approximately 600 years ago, but the largest in this volcanic field (Magill et al., 2005). Should a similar magnitude eruption occur in the future, Auckland city would be subject to a range of volcanic hazards, such as ballistic ejecta, lava flows and base surges. A probabilistic tephra fall simulation for Auckland has calculated maximum tephra thicknesses of 150 mm for the AVF, 12 mm for andesitic centres and 830 mm for rhyolitic centres (Magill et al., 2006). Eruptions from the AVF could happen without much warning – precursory activity may only be detected days before an eruption (Sherburn et al., 2007). Because Auckland is New Zealand's largest city, it is the most important economically. Having the potential to be subjected to volcanic ashfall from multiple sources with little warning, it represents a significant national vulnerability. Consequently, where this research assesses site specific infrastructural vulnerability Auckland is used as a case study.

1.5 Infrastructural vulnerability to ashfall

Few eruptions have had their impacts as frequently analysed as the 1980 eruption of Mt St Helens (e.g. Tyler and Reynertson, 1981; Schuster, 1981, Blong, 1984; Labadie 1994, Johnston 1997b, Fairchild, 2005). These studies have provided useful data on ashfall impacts, but much infrastructure has changed in the last ~30 years. Since that time ashfall from the Pinatubo 1991 eruption, the 1994 Rabaul eruption and more recently the 2008 Chaiten eruption have had significant impacts on lifelines infrastructure. Many of the impacts from these eruptions have also been described (e.g. Blong & McKee, 1995; Casadevall et al., 1996; Wilson et al., 2009). Despite these examples (and a number of less devastating eruptions) the dataset upon which we can draw to determine future impacts is not exhaustive and, as illustrated by the Mt St Helens example, is sometimes out of date. Not all impacts are addressed in the literature; for instance very little has been written about the impacts of ashfall on sewerage systems since the accounts of the destruction of Yakima's treatment plant following the 1980 Mt St Helens eruption (Day & Fisher, 1980; Johnston 1997b). Many of the hazards posed by volcanic ashfall to urban lifelines infrastructure are thus not well quantified.

1.6 Research methodology

To assess the vulnerability of the selected types of infrastructure to volcanic ash a literature review was carried out first, to establish past effects of ashfall on infrastructure. This identified potential vulnerabilities, but also indicated that there was a dearth of published data on the impacts of ash on particular lifelines infrastructure. An assessment of the infrastructure itself was performed next, to determine what exactly was at risk in New Zealand. This was followed by fieldwork in areas that had recently been impacted by ashfall. The main areas chosen for this work were Catania, Italy, and Quito, Ecuador. Both of these cities had experienced ashfall on multiple occasions in the decade prior to this. To a large extent the fieldwork involved conducting interviews with infrastructure providers and local scientists to ascertain the effects of ashfall on specific types of infrastructure. Some testing was also carried out on ash covered areas of Mt Etna.

In addition to fieldwork, laboratory experiments simulated the effects of ashfall on components of infrastructure, as without these there was insufficient data to accurately assess the vulnerability of some infrastructural components. A prerequisite for the simulation of ashfall was obtaining fine volcanic ash. As the fine components of ash are usually washed away by rainfall shortly after deposition, fine ash was not available in large quantities in New Zealand; there were no magmatic eruptions in New Zealand during the course of writing this thesis. Some small samples of fresh ash from overseas volcanoes were used in some cases, but for experiments that required several litres of ash a proxy was used. This was created from unweathered samples of local Port Hills basalt. Descriptions of this process are given in chapter 3. The resultant 'ash' proved to have a similar grainsize, grain shape and hardness as fresh samples of ash. This enabled testing of pumps and air-conditioning units. Corrosive properties of fresh ash on infrastructure were tested in most instances by fluids sampled from the September 2007 lahars of Mt Ruapehu, which were generated by a small hydrothermal explosion (BGVN, 2007).

1.7 Summary

Historic eruptions indicate lifeline infrastructure is vulnerable to volcanic ash, however quantifiable information about these impacts is lacking. The relatively small frequency of ashfall impacting urban areas has resulted in a small dataset of infrastructural impacts. Furthermore advances in technology in the last few decades have led to societal reliance on infrastructure that has not previously been subjected to volcanic ashfall. Urban centres near active volcanoes are subject to a substantial risk of being impacted by ashfall.

Through a combination of literature review, fieldwork, interviews and laboratory testing, this thesis aims to identify the vulnerabilities of selected New Zealand lifelines infrastructure to volcanic ashfall. Chapter 2 identifies and assesses risks posed to telecommunications infrastructure. Chapter 3 quantifies risks to air-conditioning units by testing them in simulated volcanic ashfall. This research came about as a direct result of vulnerabilities identified in telecommunications infrastructure. Chapters 4 and 5 address transportation, looking at aspects of the aviation sector and mobility of vehicles on ash covered roads. Lastly an analysis of the vulnerability of Auckland's wastewater system to ashfall is conducted. The information gained from this research will make possible the emplacement of improved mitigation strategies to manage the risks posed by volcanic ashfall. The concurrent studies into water and electricity supply during volcanic eruptions compliment this work, such that the outcome of the combined research will be an increase in the resilience of New Zealand communities to volcanic ashfall.

CHAPTER 2: TELECOMMUNICATIONS AND VOLCANIC ASH IN NZ.

2.1 Introduction

2.1.1Background

Telecommunications in New Zealand were first affected by volcanic activity in 1886, during the 10 June eruption of Tarawera. Ashfall from the eruption brought down telegraph poles and lines between Rotorua and Maketu. A lineman from Rotorua estimated that each pole was supporting “50 pounds of mud”, and described the lines as being “as thick as a candle with mud” (*NZ Herald*, 14 June 1886). Lightning strikes associated with the electrical disturbances created by the eruption also caused damage to telegraph lines between Maketu and Opotiki, temporarily cutting this link (*Auckland Evening Star*, 15 June 1886, p.2).

Telecommunications equipment over 120 years later has evolved considerably; multiple means of communication give us alternatives if one type of communication fails. In this sense our ability to maintain communication with distal centres/people can be considered more robust than in the 19th century. However the increased amount of infrastructure now required to maintain communications means more equipment is at risk. Although some of this equipment is seemingly well protected, the vulnerability of telecommunications infrastructure to volcanic ash has increased over time. This can be attributed to its more advanced nature (more components may fail), the interdependency of this equipment on other lifelines (power, road access for maintenance/repair etc) and the huge increase in the amount of infrastructure present. Reliance on telecommunications has grown in keeping with the increase in technology.

2.1.2 Telecommunications Infrastructure in New Zealand

Landline connections, whether voice or data (fax/internet), are established by means of copper wires connected from end users (houses, businesses etc) to roadside cabinets. Roadside cabinets have in the past been used to bring underground cables from a group of end users to the surface, to enable connections to exchanges and maintenance in a dry accessible environment. Currently Telecom NZ is upgrading and installing 3600 new cabinets via their subsidiary business 'Chorus'. The new cabinets contain a new broadband electronics platform (ISAM) which provides customers with an ADSL2+ broadband connection. Each cabinet serves up to 300 customers. (Telecom, 2008). Because of the heat generated by this equipment, these cabinets require artificial cooling, and contain a small heat exchange (air-conditioning unit) (Chorus 2008b). Subsurface fibre optic cables connect these cabinets to exchanges. (Chorus, 2008a). Figure 2.1 illustrates how cabinets connect houses to exchanges.

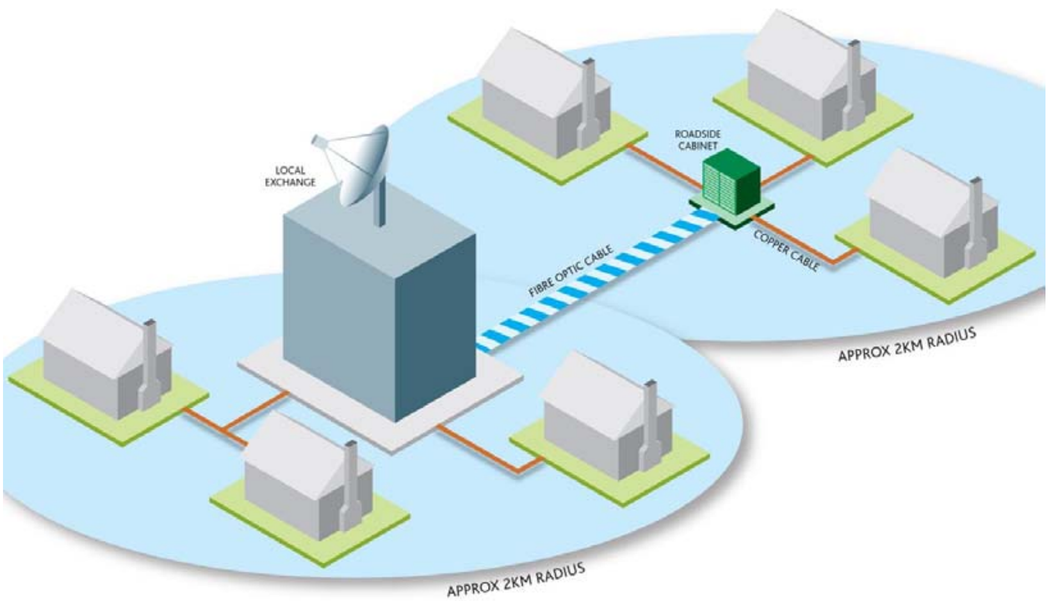

Figure 2.1: Connections through cabinets (Chorus, 2008a).

Exchanges themselves connect thousands of customers, typically whole suburbs in urban areas. Exchanges now house not only Telecom digital switchgear and ADSL2+ equipment, but are also used by other internet service providers, in some case housed in separate rooms, but sharing the same space in others. Most exchanges are unmanned, and run remotely. Exchange buildings are not built to a specific pattern;

they vary widely from weatherboard buildings with corrugated iron roofs, to purpose built concrete tilt-slab buildings, to floors within multi-storey office blocks.

Further links beyond the exchanges are made by both cables and microwave transmissions. Where cables are buried underground, no impact from volcanic ash is likely. However, roadside cabinets, exchanges, pole supported telephone lines, microwave towers and dishes will be exposed to ashfall should such an event occur.

This chapter focuses on the vulnerability of telecommunications network equipment in New Zealand to ashfall. It seeks to determine the risk ashfall could pose via impacting telecommunications equipment, or otherwise causing communications failures.

2.2 Previous occurrences of ashfall impacting telecommunications

A common impact to modern communication systems during any disaster is overloading of phone networks due to numerous people trying to contact each other at the same time. Examples of this occurring during an eruption include the overloading of the Yakima exchange during the 1980 Mt St Helens eruption (Blong, 1984), various local exchanges following the Ruapehu 1995 eruption (Johnston 1997a), and the main exchange in Quito following the 2002 Reventador eruption (Rivera, M, pers. comm., 2004).

Actual physical infrastructural damage is not as common as exchange overloads, but can include line breakages, exchanges overheating and even the complete collapse of exchange buildings. One of the earliest examples is the damage to telegraph lines caused by the 1886 eruption of Mt Tarawera mentioned in section 2.1. There have since been several instances of damage to telecommunications infrastructure. The most dramatic of these is the collapse of the almost new telephone exchange roof due to severe ash loading during the 1994 Rabaul eruption (Blong & McKee 1995). This was due to extreme loading, as almost 1 metre of tephra was deposited on it (Blong 2003). The interior equipment in the exchange was subsequently destroyed.

Breakages of telephone and power lines due to a heavy accumulation of volcanic ash occurred in Rabaul in 1994 (SMEC 1999, Blong & McKee 1995). Telephone lines were also possibly broken in Chile Chico after the 1991 Hudson eruption, though this report remains unconfirmed (Wilson et al., in review). Further impacts of ash or tephra on communication systems include impacts of volcanic ash on radio and microwave transmissions. These are addressed in section 2.3.6. Even light ashfall is thought to have occasionally caused disruptions. Approximately 1 mm of ash reportedly set off high temperature alarms in Telecom exchanges as far away as Ruatoria (~280km) during the 1995 and 1996 Ruapehu eruptions (Johnston et al., 2008).

In addition to the impacts listed above there are also several instances of areas being affected by ashfall with little or no effect on communications systems (or even air-conditioning units). For example in Japan's Kagoshima city, regular light ashfall from Sakurajima volcano is experienced. In the city most communication and electric cables are mounted on poles. These are insulated to normal Japanese standards, and appear to be unaffected by the regular light ashfall (Lorden, 2001). Exchanges also appear to be unaffected, there are no reports of communications outages and local scientists and infrastructure providers could not recall any when asked if they had occurred (Durand et. al., 2001).

These instances of impacts (and lack thereof) are important, as they indicate there are vulnerabilities in communications systems that need to be addressed. The low frequency of significant volcanic eruptions affecting urban areas from the late 20th century until the current day has resulted in a fairly small dataset, with apparent contradictions present – some telephone exchanges function normally during light ashfall while others appear to overheat and can result in shutdowns. These contradictions are addressed in chapter 3 by conducting experimental work on Telecom New Zealand exchange building air-conditioning units.

2.3 Infrastructural Vulnerabilities

2.3.1 Tephra Loading

2.3.1.1 Telephone lines

Telephone lines themselves are vulnerable to volcanic ash, simply because of the potential for line breakage. In the same way that breakages occurred in 1886 after ash and mud from the Tarawera eruption was deposited on telegraph lines, contemporary phone lines are subject to breakages after loading by volcanic ash. This may occur directly on the lines themselves, or by trees/branches falling onto them. While this type of disruption is more commonly associated with snow loading, the mechanism is the same. The amount of ash required to bring down trees in this way depends on many variables: tree type, the condition of the trees, the orientation of the branches, whether the ash is wet or dry and the amount of wind. However even without trees or other objects falling on lines, the weight of ash alone may be sufficient to break lines.

Whether ash loading alone is sufficient to break telephone lines depends on how much ash accumulates. This in turn depends on weather conditions. Dry ash is unlikely to accumulate sufficiently to cause line breakages, but damp ash may. Light rain is therefore a potential problem, as it does not remove ash, but adds to the weight. Tests on power insulators and ash adherence after the 1980 Mt St Helens eruption indicated ash would readily stick to wet surfaces, and that it took heavy rain to remove it; light rain did not remove much at all (Nellis & Hendrix, 1980). Furthermore ash could accumulate on the underside of wet surfaces. The same principles apply to ash accumulating on power or phone lines. Subsequent ashfall will exacerbate the problem if wet ash is already adhering to lines, as the ash present will provide a larger damp surface area for more ash to accumulate on.

Wind will have an effect on how much ash adheres to phone lines, both in terms of removal, and deposition from remobilised ash. Winds up to 55 km/h have been found to remove up to 95% of dry ash (Nellis & Hendrix 1980).

Most urban telephone lines or cables are now located underground, overhead lines are more often found in rural areas.

2.3.1.2 Rural exchanges and roadside cabinets

Rural exchanges and roadside cabinets have a similar construction – essentially a steel or 2.5 mm thick aluminium box mounted on a steel plinth. These are unlikely to be damaged by tephra loading due to their sturdy construction, unless indirectly damaged by other objects such as falling trees collapsing under ash loading (figure 2.2).

Figure 2.2: Rural exchange 24RU cabinet (left) and new roadside cabinet (right).

2.3.1.3 Cell phone exchanges and towers, microwave transmission towers

Many of New Zealand's cell phone exchanges are housed in converted shipping containers. These are unlikely to be affected by ash loading due to their steel construction. Other purpose built cabinets are also robustly constructed of galvanized steel, and are again unlikely to be affected in this way, unless tephra loading extreme enough to destroy almost all other nearby buildings occurs. The lack of any significant horizontal surface area on cell towers and microwave transmission towers mean that tephra loading is unlikely to be an issue in this regard (figure 2.3).

Figure 2.3: Left to right, microwave transmitter dishes and single cell site plus long wavelength antenna; Single cell site tower; 2G and 3G Telecom cell tower.

2.3.1.4 Urban telephone exchanges

While not as strong as the aluminium or steel containers and cabinets that house cell and small rural exchanges, urban exchanges are usually housed in robust buildings. Building type varies immensely; there is no standard type of exchange building. Construction types include weatherboard, brick or concrete purpose-built exchange buildings and even space in multi-storey office-blocks (figure 2.4).

Figure 2.4: New Zealand urban telephone exchange buildings. Top 2 photos © James Pole

Despite these differences most exchange buildings in New Zealand would require significant ashfall to cause collapse of the buildings or roofs – such as the 900 mm or so that caused the collapse of the exchange at Rabaul in 1994 (Blong and McKee 1995). A study on building vulnerability by Spence et al., (2005) reviewed tephra damage to buildings from several late 20th century eruptions, including Rabaul, Pinatubo and Eldfell (Heimay). This study resulted in a proposed set of European tephra fall roof vulnerability curves (figure 2.5). Table 2.1 describes the roof types classified in figure 2.5. These descriptions of roof types enable them to be used anywhere, giving an indication of possible damage to New Zealand roofs as a consequence of ashfall.

Roof Class	Description	Typical design load range	Mean collapse Load
WE (weak)	Sheet roofs, old or in poor condition. Tiled roof, old or in poor condition. Masonry vaulted roof.	Pre-design code, or no design code.	2.0 kPa
MW (medium weak)	Sheet roof on timber; average quality; average or good quality tiled roof on timber rafters or trusses. Steel or pre-cast reinforced concrete joists and flat terrace roof.	1–2 kPa	3.0 kPa
MS (medium strong)	Flat reinforced concrete roof not all above characteristics; sloping reinforced concrete roof. Sheet roof on timber rafters or trusses, good quality and condition, designed for cyclone areas.	2–3 kPa	4.5 kPa
ST (strong)	Flat reinforced concrete roof designed for access; recent, good quality construction, younger than 20 years.	>3.0 kPa	7.0 kPa

Table 2.1: Proposed classification of European roof types for tephra fall resistance (from Spence at al 2005)

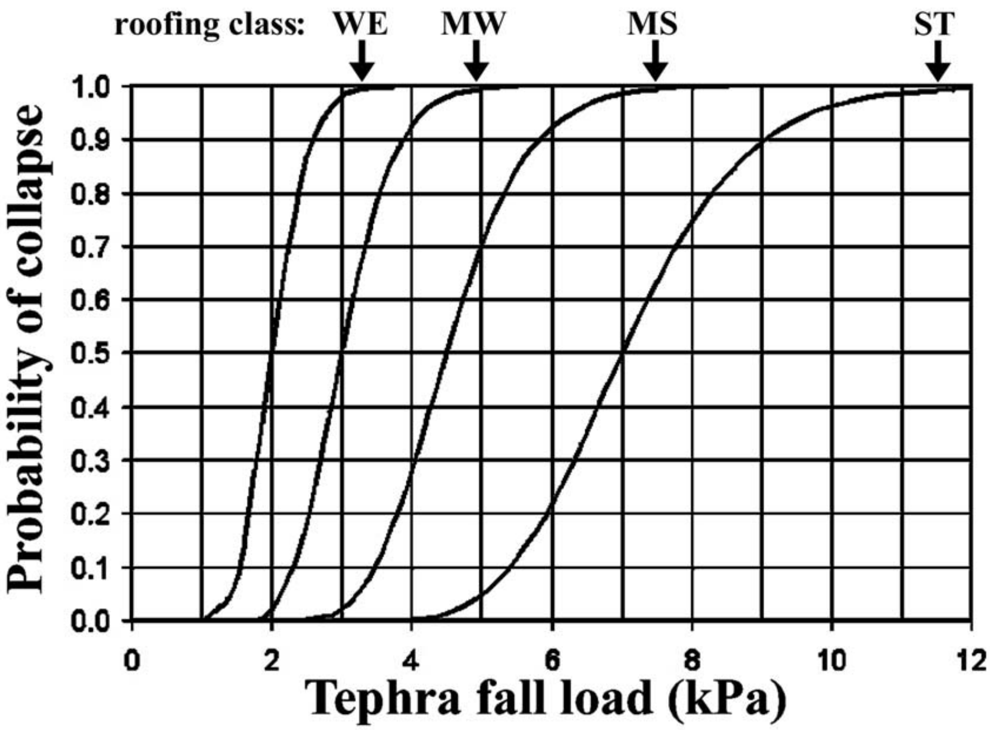

Figure 2.5: Tephra fall roof vulnerability curves for the European roof classes described in table 2.1. From left to right, classes WE, MW,MS and ST. (From Spence et al., 2005)

The depth of ash required to generate these kinds of pressures depends on the density of the ash, in turn determined by how vesicular it is, it's mineralogy, grain shape, grain size, and the moisture content of the ash. This means densities can have a wide range. For example the Rabaul eruption included tephra from both Tavurvur and Vulcan, wet tephra density from Vulcan was 800 to 1000 kg/m^3, Tavurvur was 1700 to 1900 kg/m^3. Tephra from Pinatubo (1991) had a density of 1200 to 1600 kg/m^3 dry and 1500 to 2000 kg/m^3 wet (Spence et al., 2005). These densities then need to be converted into tephra load to enable consistency. Tephra load (Pa) = ρgh,

g=Gravitational acceleration (9.80665 m/s^2), h=Tephra thickness or depth (m), and ρ=Tephra density (kg/m^3). (Spence et al., 2005)

Therefore the densities mentioned above would represent a range of pressure for a cubic metre of ash from 7.9 kPa (800 kg/m^3) to 19.6 kPa (2000 kg/m^3).

Using these figures, for a roof in the MS category listed in table 2.1 (a category which includes many NZ roofs), the mean collapse load can be estimated to be 4.5 kPa. If subjected to wet ash towards the heavy end of the scale, with a density of 2000 kg/m^3 this would represent around a 23 cm deep thickness of ash. These figures are to be treated with caution, as it may not take this much ash to cause collapses. Factors influencing this include the fact that ash can drift, causing a higher load on some parts of a roof than others, it can also slide from higher pitched roofs and impact lower roofs. Wide span roofs are more subject to collapse than smaller structures, more steeply pitched roofs fare better than flatter roofs (Blong & McKee, 1995). Structural failure may also occur to supporting columns or walls (Spence et al., 2005). Furthermore it does not take a complete failure and collapse of a roof for partial areas of buckling or a small collapse to allow ingress of ash into building interiors (Blong & McKee, 1995). This can also result in the entry of water into buildings during rainfall.

Most exchange buildings in New Zealand fall under the MS or ST categories, and do not tend to have large span roofs. Some older weatherboard buildings used as exchanges may be closer to falling under the MW category. It would require a significant distal eruption or one close to an exchange - e.g. an eruption in Auckland, to cause roof or structural collapse in urban telephone exchange buildings, however ingress of ash could occur to less robust exchanges with much less ash. For example, assume an older exchange building constructed of timber frame, weatherboard and corrugated iron that fell under the MW category. A load of 2.5 kPa would generate a 20% chance of roof collapse. This represents an ash thickness of just over 12 cm using a heavy wet ash with a density of 2000 kg/m^3. Even if the roof survived largely intact, only small amounts of buckling would be required to cause leaks. This could in turn be catastrophic for electronic equipment housed within. For this reason it would be advisable to clean exchange rooftops once ash thicknesses exceeded a few centimetres. This procedure necessitates extreme caution, due to both the slipperiness of the ash, and the addition of the weight of cleaners on a potentially overloaded roof.

2.3.2 Ash ingress to exchanges

Without structural or roof damage occurring to exchange buildings, and provided backup fresh-air intakes are not used or doors and windows are not left open for any length of time, only very small amounts of ash are likely to enter these well sealed buildings. However should any of these occurrences happen, there would be a strong possibility of equipment failure, depending on the quantity of ash getting in. Fine particulates less than 2.5 microns in diameter are especially problematic. Accumulations of particles may bridge gaps between conductors. If these particles are damp, or humidity is sufficient to rise above the deliquescence point of attached salts, the moisture may cause current leakage, (possibly leading to cross-talk and line noise in analogue systems) or even electrical shorts (Weschler and Shields, 1991). The addition of moisture to ash has been found to be problematic in tests performed with other computer equipment. Dry ash is less conductive, but the increased conductivity of wet ash results in more failures (Gordon et al. 2005). Contacts and connectors covered in fine coatings of ash may also result in failures, if relays “mate” as ash bridges connect them. Corrosion of components is likely to be a problem, as is connector wear if any cables are inserted or removed (Weschler and Shields, 1991). The removal and insertion of cables is no longer usual practice in modern (unmanned) exchanges as it was in older manned exchanges, where cables were manually moved around to connect calls.

2.3.3 Air conditioning and cooling

The most important vulnerability associated with exchanges, less extreme than building or roof collapse, but much more likely to be problematic is the need for cooling. All exchange types need cooling, but fresh air vents are not sufficient to achieve this. Some older rural exchanges (cabinets) have used fresh air fans in the past, but these are being replaced with air-to-air heat exchanges (air conditioners). Cell phone exchanges, urban exchanges and new roadside cabinets all require air conditioning, in some cases augmented by fresh air fans if air conditioners cannot provide sufficient cooling. The vulnerability of air-conditioning units to volcanic ash, and the effectiveness of any fresh air filtration systems is therefore a critical factor in determining how robust exchanges are when it comes to volcanic ash. The performance of air conditioners in ashfall is examined in chapter 3, using equipment sourced from urban telephone exchanges.

2.3.3.1 Cell phone exchanges

While tephra loading is unlikely to be an issue for cell phone exchanges, the need for air-conditioning is. Exchanges routinely have blockages occurring in the air-conditioning intakes and condensers, due to dust and any airborne matter blowing around as a matter of course. These are regularly serviced and cope with small amounts of dust and debris. The amount of material (ash) potentially received during an eruption will far exceed usual amounts of dust and debris.

Cell sites typically have two split system air-conditioning units present, one of which acts as a backup (figure 2.6). Each unit has a cooling capacity of about 6KW, which equals the amount of internal heat produced within the exchange. Normal operating temperatures are below 25^{O}C. Once internal temperatures exceed this amount the second unit starts up (D. Johns, pers. comm., 2009). This means that under normal circumstances the available cooling capacity is 12KW, or 200% of internal heat generation. Until the efficiency of both units drops below 50%, the two air conditioners running simultaneously should be able to maintain production of sufficient cool air to enable the exchange to keep running.

Figure 2.6: Cell phone exchange air conditioners.

Testing of air-conditioning units (as described in chapter 3) indicates that even in heavy ashfall, the performance of such units will not necessarily drop below this amount. This will depend on compressors restarting automatically after shutdowns due to overloads. Even if compressors do restart automatically, should overloads in the two air conditioners occur simultaneously, internal temperatures may rise above $30^{O}C$ within minutes. Compressor overloading is likely to occur sporadically after an ashfall exceeding 30 to 50 mm (section 3.5.8). This will depend on weather conditions, and may be sooner if ambient temperatures are significantly higher than $22^{O}C$. Once internal temperatures reach $30^{O}C$, which will likely happen if the air-conditioning units fail, fresh air fans turn on and draw outside air into the exchanges (D. Johns, pers. comm., 2008). There is no remote dial up to stop this occurring; they can only be disabled on site. The outcome of an intake of ash-laden air into exchange interiors will be potentially catastrophic for internal equipment, especially if moisture is also to enter the interior. This will cause the ash to become conductive (Gordon et al, 2005), resulting in bridged connections, short-circuits and otherwise damaging internal components. Communications failure through the site is very likely in this situation. Alternatively, disabling the fresh air intakes will protect equipment, but internal temperatures will continue to rise. At $35^{O}C$ a second high temperature alarm is triggered, but this does not affect the exchange in any way; there is no automatic shut down (D. Johns, pers. comm., 2009). As temperatures rise above $35^{O}C$ fault connection errors in data transfer begin to increase and data transfer speeds slow down. Above ~$55^{O}C$ there is a risk of damage or failure to chips, capacitors, conductors and semi conductors. In most instances power supply rectifiers will keep functioning at temperatures as high as 55 ^{O}C or $60^{O}C$ for several days, but eventually they may be damaged operating at these temperatures. Some damage may not be evident for days, weeks or even months, but in a worst-case scenario rectifiers will fail during elevated temperatures, resulting in power loss to the exchange. Batteries will supply power for 2 - 8 hours, depending on the site. It is not only the performance of the air conditioner and ambient temperature that will affect internal temperatures; high loads, or call volumes will also increase temperature. Quiet exchanges may thus sustain less damage than busy exchanges. The servicing or cleaning of air conditioner units during ashfall to prevent condenser blockages occurring will help to prevent disruptions, but the practicalities of getting staff to cell sites to do this during an eruption makes such action problematic. Once ashfall has ceased, it will still be necessary to increase servicing of air conditioners, as long as ash is present on the ground. Wind and/or human activity (vehicles etc) will remobilize ash, making it likely that more ash will be entrained into condensers.

2.3.3.2 Urban exchanges

Other than fresh-air intakes, used as backup in the event of air-conditioning failure, urban telephone exchange buildings in New Zealand are generally well sealed, having very little influx from outside air. Provided doors and windows remain closed, ash is unlikely to get into the buildings in significant quantities - unless the fresh air-intakes are used, or structural/roof damage occurs. Significant amounts of heat are generated with the buildings though, due to the amount of electronic equipment housed within. This same equipment needs to be kept cool; the normal operating range is between 15 and 30^{O} C. Cooling is achieved by means of constant air-conditioning, using multiple air-conditioning units. Without this input telephone exchange interior temperatures would rapidly climb. 40^{O} C would be reached in 5 to 15 minutes, depending on the exchange and the start temperature (D. Johns, Downer Engineering; S. Ross, Telecom, pers. comm. 2006). High temperature alarms are generally set to 35^{O} C in exchanges, including cell-phone exchange sites. This temperature is not sufficient to immediately cause problems, though some equipment is likely to fail if these temperatures last for several days or more. Once 55^{O} C or 60^{O} C is exceeded more problems begin to occur - for example displays on rectifiers stop functioning (pers. comm. D. Johns). As temperatures rise there is also an increased fire risk to consider.

For the above reasons air-conditioning units are indispensable; exchanges may not operate for long without being cooled. In the event of air-conditioning failure, most exchanges would soon shutdown. All voice and data communications routed through those exchanges would subsequently cease. The majority of air conditioners used in NZ exchanges are split system types, which testing indicates are vulnerable to failure once ashfall exceeds 30 mm (chapter 3).

2.3.3.3 Fresh air intakes

Fresh air intakes are present on many exchanges, but are only used as a backup for when air conditioners fail. The filtration used for these is usually EU3 media, which was found to let fine particulates through, before blocking up with ash (section 3.5.10) Filters are not designed to cope with the amount of ash that may be present in the atmosphere during ashfall. Fresh air intakes must be manually switched off in the event of an ashfall. Any overheating and short-term shutdown as a result will be preferable to long term damage caused by the influx of volcanic ash. Short term inconvenience is preferable to long term communications failures and expensive refits.

2.3.3.4 Rural exchanges

Rural exchanges vary depending on the size of the communities they serve, but are typically housed in small cabinets, such as the 24RU cabinet in figure 2.2. Cooling is effected by two different means depending on the age of the cabinet. Older cabinets use a small fan, which draws in outside air to the cabinet through one layer of filter media, newer cabinets use a separate internal and external fan with a heat exchanger in between the two. Unfortunately neither cooling system was available for testing during the course of this research. However testing of filter media during larger scale air-conditioner testing (chapter 3) indicates that the use of fresh air fans and filters is likely to result in both initial ingress of ash to the exchange and eventual blockage of the filter. This may result in bridged connections and component failure due to conductive ash causing shorts, then overheating as the filter becomes blocked. Newer sealed units should not be affected by ash ingress, but the exterior part of the heat exchange may become blocked with ash, depending on ash grainsize and airspeed. Once temperatures exceed 47^{O}C a high temperature alarm triggers, automatic shutdown of equipment occurs at 54^{O}C, and requires a manual power reset.

2.3.3.5 Roadside cabinets

The requirement for cooling in roadside cabinets creates a potential vulnerability to volcanic ashfall. Overheating would result in shutdown of the cabinet, terminating communications for those end-users each individual cabinet provides for.

Internal temperatures in roadside cabinets are usually between 30^{O}C and 40^{O}C, depending on ambient air temperatures. Cooling is effected by an air to air heat exchange, rather than an air conditioner. Exterior (unfiltered) air is blown between sets of aluminium fins, cooling them as it passes between them. On the other side of each fin warm interior air is circulated, and is cooled as it does so (figure 2.7). This type of heat exchange is rated to 1300W, and is designed to keep the unit running at no more than 10^{O}C above ambient temperature. Internal heat produced may be as much as 1200W, but units usually run at 600-800W. No exterior air is introduced to any internal part of the cabinet except for the heat exchange.

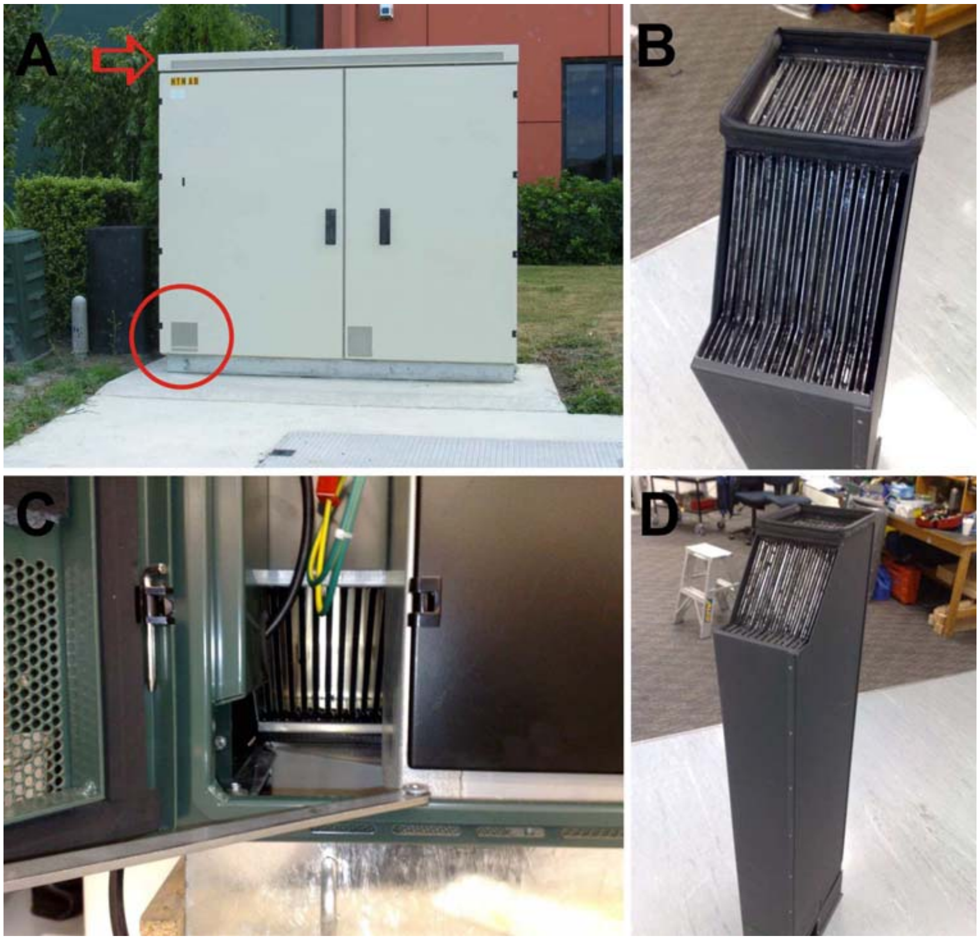

Figure 2.7: A. Telecom roadside cabinet, arrow indicates air outlet, circle indicates location of intake for heat exchange unit (C). B. Close up of heat exchange unit (D).

The lack of a need for refrigerant or a compressor makes this type of cooling more resistant to volcanic ashfall than air conditioning. While intakes are positioned close to the ground (figure 2.7), air may also be drawn in through the outlet vent at the top of the unit. Therefore if a thick deposit of ash blocks the base of the unit, air may still be drawn into the heat exchange. Although lowering efficiency, some cooling would still be effected. The bases of the intakes are located 12 cm above ground level, requiring heavy ashfall or significant drifting of ash to cause this type of blockage.

Ingress of ash to the heat exchange may also cause blockages, and decrease efficiency. Airspeed at the intakes was measured at 8 km/h. At this speed ash will be drawn into the heat exchange, but would then have to travel over one metre upwards to escape. While this will be possible for fine ash, coarser particles may be trapped within the base of the exchange, eventually blocking the intakes, causing the exhaust vent at the top of the unit to also act as an intake, again lowering efficiency. The time taken for this to occur will depend on ashfall rate and grainsize. Should temperatures rise to $50^{O}C$ a temperature alarm will be triggered, at $55^{O}C$ shutdown would occur, preventing heat stress to equipment (C. Gilmore pers. comm., 2009). Once this shutdown has occurred, a manual restart is required.

While fan failure is unlikely, should this happen to one fan, the other fan will switch to its maximum setting. An alarm will then be triggered informing the telecommunications company of this occurrence – assuming communications networks are functioning.

2.3.4 Lifeline dependency - Electricity

To run exchanges, power is necessary. However power failure is common during ashfall. This can occur either through line breakage (e.g. in Rabaul in 1994 (Blong & McKee 1995), Chile Chico 1991 (Bebbington et al., 2008)), or insulator flashovers causing short circuits and thus outages (e.g. Ruapehu 1996 (Johnston et al. 2000) Mt St Helens 1980 (Sarkinen & Wiitala 1981)).

2.3.4.1 Rural exchanges

Rural exchanges rely on batteries to keep them functioning in the event of power-cuts. In this way they are vulnerable to volcanic ash, and will cause telecommunications failures should a power cut longer than 8-12 hours occur, depending on exchange type (S. Ross pers. comm., 2009). In some rural areas Telecom has installed sockets that allow local farmers to plug in portable generators to power exchanges. These are a contingency for heavy snowfall, and as such are situated in areas likely to be affected by snow (South Island), rather than most North Island sites likely to be affected by ashfall.

2.3.4.2 Roadside cabinets

Roadside cabinets are mains powered, but have backup batteries in case of power failure. Batteries in newer whisper cabinets will keep the cabinets operating for 11 hours when the unit is operating at full load. Since most cabinets operate at less than maximum capacity, battery life may exceed this by a few hours. Some older cabinets may have slightly more or less battery life than this. For example Powerware N750 cabinets have approximately 12 hours battery life, SATCAB600 cabinets have up to 8 hours battery backup (Eaton Powerware, 2009).

In addition to battery backups, most cabinets also have a generator inlet. These allow not only the telecommunications companies, but anyone with access to a generator to power the cabinets in the event of an emergency. The generator socket is a standard 3-

pin plug type, and access to the socket is behind a small panel, which can be opened with standard allen or hex keys. This allows any member of the public to provide power to the cabinets should the need arise.

2.3.4.3 Cell sites

Power supply may also be an issue for cell sites during ashfall. Battery backups are designed to last for up to 2-4 hours in urban areas, and 5-8 hours on rural cell sites (D. Johns, pers. comm., 2008). Power failure due to ashfall may be widespread, faults may affect multiple parts of the network, therefore restoring power could take several days. While it would be impractical to have battery backups that can last this long, this needs to be factored into the planning for such an event.

2.3.4.4 Urban exchanges

Backup diesel generators are available at most urban exchanges. In most instances these draw in outside (unfiltered) air, so ash ingestion is likely to be a long term problem. Short term use is possible, assuming air-filters on the generators are regularly cleaned. Should ashfall affect power supplies by disrupting distal power sources/supply lines, without directly affecting the exchange, the backup generators should function as well as they would in any other power cut. However their reliability can possibly be questioned. This was aptly demonstrated on November 4th 2007, when a power outage (due to a cable fault) at Auckland's Mayoral Drive data centre closed down that exchange for several hours. The temporary closure of the exchange caused disruptions to 15,000 broadband, mobile and dial-up customers – not just from telecom but from numerous service providers (McNaughton, 2007). Those with pagers (including the emergency services), were not able to use them. Eftpos transactions and other computerised communications around New Zealand failed for much of the day (Schouten, 2007). As far away as Christchurch, police southern communications staff were required to use pen and paper to record details and paper maps to pinpoint locations, when their computer system failed as a result of this loss in communications (McNaughton, 2007).

This power-cut occurred despite backup generator systems being available in the exchange. In an ashfall event, there is therefore a strong possibility that power-cuts could cause problems for telecommunications, given that several exchanges may be affected by ashfall at the same time. This will not only stretch resources, but if ashfall is directly impacting exchanges, access is likely to be hampered by the presence of both airborne ash and ash covered roads (chapter 5). While some back up systems will work, there is a significant chance that some of them will not, as demonstrated by the events of November 4 2007. This in turn would lead to network failure until power could be restored.

2.3.5 Corrosion

Corrosion is only likely to be an issue in the long term. The low pH commonly associated with volcanic ash results in acidic leachates, most commonly containing sulphuric acid (H_2SO_4), but also potentially hydrochloric acid (HCl) and sometimes hydrofluoric acid (HF). These react with most metals, including aluminium and iron – both commonly used in telecommunications infrastructure. Ashfall induced corrosion is common during and after eruptions (e.g.; Blong, 1984; Blong & McKee 1995; Johnston, 1997a; Matsumoto et al., 1988). In terms of telecommunications infrastructure, roadside cabinets, rural and cellphone exchange cabinets and housings are painted, and are not expected to be adversely affected. Exposed roofing iron and gutterings on urban exchanges may suffer from some corrosion, depending on leachate pH, weather conditions and whether roofs are painted or galvanised. Air-conditioning condensers are aluminium, and will be subject to oxidation, and potentially pitting on the aluminium fins. Transmitters/antennae on towers are also potentially at risk, and will need to be inspected after ashfall, painted surfaces will be protected but any exposed metal will quickly be affected by corrosion.

2.3.6 Radio / Microwave transmitters and transmissions

Radio antennae, microwave towers and dishes are situated outdoors and thus may be exposed to ashfall. While vertical antennae are unlikely to accumulate much ash, insulators on antennae can. This occurred during the 1980 Mt St Helens eruption, when Teflon insulators shorted out due to being covered with ash. They were replaced with ceramic insulators, which were more resistant to ash induced flashover (Labadie, 1983). Microwave dishes and components such as feed horns and wave guides may also accumulate ash deposits. Covers for dishes provide a simple mitigation option. These are currently used on microwave dishes close to Sakurajima Volcano in Japan, an area which experiences frequent light ashfall (Durand et al 2001). Ash accumulating in microwave dishes can be problematic in two ways; corrosion or oxidisation of the aluminium dish can occur as acidic volcanic ash reacts with the aluminium. Additionally signal loss may occur due to the covering of conductive ash on or in the aluminium dish (S. Oldfield, pers. comm., 2007). This necessitates the availability of staff during and after ashfall to clean ash from equipment to maintain as much functionality as possible. Simple plastic tarpaulins can be used to good effect in covering transmission equipment (Labadie, 1983).

Some remote transmission sites use solar power. This power source will be compromised in ashfall, as ash will cover solar panels, depriving them of light. This needs to be considered in response planning to avoid cutting off isolated communities.

Of immediate concern during ashfall is the potential for radio and microwave signal attenuation. Exactly how a particular ashfall will affect radio signals is largely unknown, or at least unpredictable. A few instances of ash clouds interfering with radio traffic have been recorded, yet there have also been many ashfalls where no disruption to radio transmission has occurred or been noted. A few examples of radio being affected include communications from Kodiak Island being rendered inoperative for several days following the 1912 Katmai eruption, (the island is 160 km from Katmai) (Erskine, 1962). During the 1963 Surtsey eruption radio static from the ash cloud was picked up by a passing ship (Anderson *et al.* 1965). Some radio traffic was affected by electromagnetic disturbances caused by volcanic ash during the 1991

Pinatubo eruption (Rodolfo 1995). The large amount of electrically charged ash that can be generated in an eruption column is likely to be responsible for this interference.

Examples of the many more eruptions where radio communications have not been affected in this way include the 1980 Mt St Helens eruption, the 1995 and 1996 eruptions of Mt Ruapehu, the 2002 eruption of El Reventador and the numerous eruptions from Sakurajima during the 20th century until present day. Further unreported instances of a lack of impacts of this sort are likely.

Why radio traffic is affected by some eruptions and not others can be attributed to the large number of variables involved. Signal wavelength and strength will in part determine the amount to which it is affected by an ash plume or ashfall (this effect is mirrored by other types of radio interference such as dust storms or rain). A direct example of this happening in ashfall occurred during the 2002 eruption of Mt Etna, when INGV *(Istituto Nazionale di Geofisica e Vulcanologia)* staff attempting to use handheld radios from near the active vent could not communicate with the INGV observatory in Nicolosi. The attempt to communicate was made from the same location in similar weather conditions to the day before, when radio communication was possible. The only difference was the presence and location of the ash plume from the volcano. When two-way radio communication failed cell phones were used instead – these functioned normally despite the presence of the plume (Barnard, 2004). Cellular phones use part of the UHF (300–3000 MHz) frequency. Hand-held radios, depending on type can be HF (3–30 MHz), VHF (30–300 MHz) or use a different part of the UHF range to cellular phones. The only variable in play – the presence of the ash plume – was the reason that the hand-held radio signal failed. The fact that at the same time the signal from the cell phone worked without interference is attributable to the use of a different (in this case higher) radio frequency by the mobile phone.

In August 1991, ashfall from the Mt Hudson eruption caused satellite communications to fail in Los Antiguos, 120 km from the volcano. 80-100 mm of ashfall was recorded here (Narajo and Stern 1998). Although the satellite communications failed, HF radio, (using much lower frequencies) reportedly kept working(Wilson et al. in review).

Radio signals, especially in the higher frequency ranges (SHF and EHF, 3-30GHz and 30-300GHz respectively), are adversely affected by the presence of atmospheric particles (Crane, 1971; Elabdin et al., 2008 a, b). It is this range that microwave transmitters utilize. Microwave signals can include television broadcasts, cell-phone calls, and wireless internet connections. Other users of these frequencies include satellite links (including sky digital television) and door openers. Microwave links have been tested in Sudan duststorms, and such transmissions have been found to undergo significant attenuation (Elabdin *et al* 2008a). This is particularly the case with signals in the microwave band and higher frequencies (> 3GHz). With visibilities under 200 m, attenuation increases rapidly with decreasing visibility (Ghobrial & Sharief 1987). Particle size will also have an effect on signal strength (Elabdin et al, 2008b). Exact effects are again dependant on wavelength.

To an extent dust-storms can be used as an indicator for ashfall effects in regards to radio signals. However there are further complications during ashfall. The Sudanese dust storms tested were dry, ashfall may contain moisture, or can occur during rainfall (which also has an effect on signal attenuation). As frequencies increase, attenuation from rainfall becomes worse (Rahman & Leng 2003). Another complicating factor is the electrical charge which can be generated in an ash column (e.g. Gilbert et al 1991, Gilbert & Lane 1994). The lightning associated with this has in the past been recorded as being more problematic than the ashfall itself for microwave communications. Towers have been struck and damaged or destroyed by lightning during eruptions, cutting communication links. This occurred during the 1991 Hudson eruption, when many HF and VHF radio receivers were hit and put out of action by lightning strikes (Wilson et al, in review).

While dust storms cannot be used as a direct analogue to ashfall they can still serve as an indicator of potential signal attenuation. When compared to a given dust storm, it is expected an ashfall of a similar concentration and grainsize will have a more severe impact on signal attenuation, due to its increased moisture content and electrical charge.

Although testing of signal attenuation has been conducted with dust-storms, testing this under ashfall conditions is not a practical option. The variables which can affect the signal (ash concentration (visibility), ash grainsize, water content and electrical charge) will differ in every eruption, so predicting what signal loss may occur would be very imprecise. Access to suitable equipment and eruptions also make this type of testing unfeasible.

Should signal loss occur during an eruption it will be widely felt by those in the afflicted area. The use of cellular phones depends on radio signals travelling to and from mobile phones to cell phone towers, and in some areas microwave transmissions from cell towers. Cell phone towers in urban areas are usually linked to exchanges via fibre-optic cables, the larger distances between towers and exchanges in rural areas mean that microwave links are more cost effective and thus more common in these areas. Microwave transmissions are also used by broadcasters; television signals therefore have the potential to be disrupted. However this type of interference is limited to the time ash is falling. A small amount of maintenance – such as cleaning microwave dishes of any accumulated ash - may be necessary to keep communications working. Unless physical damage occurs to equipment, effects of ashfall on radio signals will be limited to the time ash is airborne. This may still be problematic for emergency responders as during emergencies radio is an important means of communication for authorities.

2.4 Summary of potential impacts to telecommunications infrastructure.

Telecommunications infrastructure is robust enough that it is unlikely to be adversely affected by light ashfall unless power failure occurs. In this event battery backups will maintain communications for 2-12 hours, depending on exchange or cabinet type. Generators are available for some exchange types, and generator inlet sockets are present on new roadside cabinets. Without power, communications failure through exchanges and roadside cabinets will occur. Heavier ashfall poses more risks to communications infrastructure. In most instances this is due to the need for constant cooling of communications equipment. A threshold of ~30 mm of ash has been established for split system air conditioners. Above this amount of ash the likelihood of failure swiftly increases (chapter 3). Exchanges do not use this type of air conditioner exclusively, and some cooling systems will be more robust, however this type is commonly employed on urban and cell phone exchanges. Overheating of exchanges may lead to component damage followed by exchange failure, or automatic shutdowns, again depending on exchange type. Automatic engagement of fresh air fans in cell sites once temperature thresholds have been exceeded will be catastrophic for equipment. The capacity to address these issues during ashfall needs to be addressed in any telecommunications company’s response plan.

In addition to impacts on cooling systems, heavy ashfall may be problematic for urban exchanges, since ash can block gutterings and downpipes, causing water to leak into buildings in the event of rain. Depending on roof type, after a few centimetres of ash exchange roofs may be damaged or collapse, harming or destroying exchange equipment in the process.

As most ashfalls are light, the main risks to telecommunications networks are overloading and power loss. Vulnerability associated with power loss is unavoidable, as providing backup generators for all exchanges and cabinets is not practical, and battery backups will always be a temporary solution. However in most cases, if robust response plans are prepared before, and acted upon during the event, direct impacts of ash on telecommunications infrastructure need not cause failure. The exception to this may be during ashfall in excess of ~15 centimetres. Response to physical impacts will then become dependant on the ability of staff to get to work, and from there getting to exchanges over ash covered roads. This issue is addressed in chapter 5.

CHAPTER 3: AIR CONDITIONER PERFORMANCE DURING ASHFALL

3.1 Introduction

The use of air-conditioning became widespread from the 1950's onwards. Since then, instances of more than a few millimetres of ashfall impacting developed areas have been rare. Globally there have been several examples of light ashfall, but the performance of air conditioners has not always been recorded in these instances. Where heavy ashfalls have caused building or roof collapse air conditioning performance has not been applicable. In cases of light ashfall it is not always apparent whether impacts are simply unreported or not significant enough to notice. For these reasons the vulnerability of air conditioners (heat exchangers) to ashfall has hitherto been largely unknown. Their importance exceeds simply a need for comfort in homes and offices; air-conditioners are a vital infrastructural component for many industries and lifelines. Examples include:

- Telecommunications exchanges. These cannot function without artificial cooling; all exchange types and cell sites require constant air conditioning.
- Waste water systems. Modern systems are dependant on air-conditioning to cool computer control systems. For example Auckland's waste water treatment plant at Mangere could not function without air conditioners, due to the high level of heat generated by computers in it's control room.
- Refrigerated warehouses containing frozen foods or medicines etc are completely dependant on air conditioning for refrigeration.
- Large commercial or public buildings. Some large buildings are designed with glass facades to provide both views and a lot of light, but also capture so much incandescent heat that air-conditioning is necessary to keep interior temperatures bearable. As an example, temperatures in Auckland International Airport's international terminal would quickly climb to well above 40^{O}C without air conditioning (Robertson, R. pers. comm., 2005).

3.2 Examples of air-conditioner use in ashfall

An area that frequently receives light ashfall is Kagoshima, Japan. Kagoshima city lies approximately 10km to the west of Sakurajima volcano. Until 1990 ashfalls occurred up to twice per week in the city; they continue to do so but at a less frequent rate. These ashfalls are usually light; a 5 mm covering of tephra would be considered an extreme event. Exterior mounted air-conditioning units are prolific in the city, and have no special protection; these also apparently function well despite frequent ashfall (Durand et. al., 2001).

A similar situation exists in Catania, Italy located on the lower slopes of Mt Etna. Catania is frequently subject to ashfalls of up to a few millimetres, particularly over the last decade. As with Kagoshima, air conditioners have no special protection, and still function normally. This was confirmed by interviewing maintenance staff from several hotels in Catania, who reported a lack of problems when asked about the impacts of ashfalls from Etna on their air-conditioning systems (Pensione Ferrara, Katane Palace, Liberty hotel, Grand Excelsior hotel). Another hotel reported having service personnel regularly clean the units after ashfall, but had not noticed any adverse effects (hotel maintenance staff, Jolly Hotel, Catania pers. comm., 2005).

While Catania and Kagoshima provide examples of how communications systems can continue to function well during an ashfall without any special protective measures being taken, there are examples of air-conditioning systems at telephone exchanges being affected by very light ashfall. Approximately 1 mm of ash reportedly set off high temperature alarms in a Telecom exchange in Ruatoria during the 1995 and 1996 Ruapehu eruptions (Wilson et al., 2009). A similar problem was reported after the 1992 Mt Spurr eruption. Air conditioning intakes in Anchorage experienced blockages, resulting in all air-handling units being manually shutdown after an ashfall of approximately 3 mm thickness. Fortunately the cool temperatures experienced in Alaska were sufficient to prevent exchange temperatures reaching critical levels and necessitating shutdowns (Johnston, 1997b). This shutdown performed manually, to prevent expected damage, rather than a result of actual damage to systems.

The eruptions of Chaiten Volcano in Chile (2008-2009) have recently given an example of more than a few millimetres of ashfall impacting developed areas. From the 2nd to the 6th of May 2008 approximately 60 mm of very fine ash was deposited on a cable television relay building 100km from Chaiten, in the town of Trevelin. Local technical staff reported that there was no impact on their air conditioner performance; it kept functioning normally, and had no protection aside from a foam rubber pad placed over the top to shelter it. No additional maintenance was required afterwards (Wilson, T pers. comm., 2009). The unit type was a through-wall design, which is an older design, and though still used is not as common in New Zealand as conventional split system units (figure 3.1).

Figure 3.1 Air conditioning unit used in Trevelin, Chile, subjected to 60 mm of ash with no adverse impacts.

These instances of units continuing to operate effectively in ashfall conditions, seem to contradict those reports of them being affected by a few millimetres of ash. To understand how much (if any) ash would impact air conditioner performance it was necessary to test air-conditioners with volcanic ash under laboratory conditions (section 3.5).

3.3 How an air-conditioning unit works

Air-conditioning units use a refrigerant such as *Freon*. This is mixed with a small amount of lubricant oil, then compressed in the air-conditioning unit compressor. This causes it to become a hot, high pressure gas. The hot gas is run through a series of coils (the radiator or condenser) which are situated in front of a fan. Heat is dissipated via these coils and the fan to the outside of the building. As this process takes place the refrigerant rapidly cools and condenses into a liquid. The liquid is run through an expansion valve, at which point it evaporates to become a cold low pressure gas, of approximately -40^{O}C, depending on refrigerant type. This gas then moves through another series of coils (the evaporator) situated inside the building. A fan behind these coils blows air across the cold coils, subsequently cooling it. The process is cycled. In this way air can be cooled without the need for introducing fresh air from outside the building. Inverter units operate under the same principle, but whereas a standard air-conditioner will start and stop depending on whether the required temperature has been reached, an inverter will keep running, but modulate the strength of the compressor to create more or less cold/hot air as required.

3.4 Previous work

Previous testing of air-conditioners with volcanic ash was conducted by Wilson, (2005). This testing was undertaken to help evaluate the vulnerability of dairy farming operations to ashfall. Tests used an air-conditioner fan and radiator to determine whether the radiator could be blocked with volcanic ash. The testing was conducted inside an enclosed perspex box, recycling all air and ash. Small fans were employed to keep ash remobilised. While some ash would settle on the ground, most would be recycled through the unit. As the experiment progressed more ash was added. The compressor and condenser were not operating, so no heating or cooling of air was taking place, other than heat generated by the fan motor. As no cooling or heating was taking place, the effectiveness of the unit in cooling warm air was not being measured, rather the propensity of the unit to become blocked with ash. However the confined space that the unit operated in would have affected the airflow through the unit considerably, and ash that had not been trapped in the unit would be continuously re-entrained. An equivalent amount of ashfall that the unit had been subjected to could not therefore be established from this type of testing, nor could unit efficiency under ashfall conditions be quantified. Wilson (2005) did find that it was possible for air-conditioning units to be blocked up by tephra, especially if water was involved, but the amount of ash required for this to happen was not established.

3.5 Air conditioning testing

3.5.1 Introduction

The objective of this testing was to establish how effective air-conditioning units are when functioning in an ashfall, and whether they can continue to provide cooling under such conditions. The amount of ash required to cause a drop in efficiency (if any) was sought, as were ways of mitigating any effects. Determining whether or not they would completely fail due to ashfall was the final goal.

The widespread use of air-conditioners by commercial, industrial and domestic users gives this research a wide application. The units tested were sourced from Telecom NZ exchange buildings. While typical of those found in exchanges, they are not of a type specifically found only in telephone exchanges, but are commonly used worldwide in many commercial and industrial applications, and in some areas for residential heating and/or cooling.

The testing conducted did not seek to determine the long-term impacts of ashfall on air-conditioning units, but whether they could continue to function if used during ashfall or while ash was entrained in the atmosphere. This was for several reasons.

- The value and importance of equipment and goods cooled by air conditioners in commercial and industrial settings (e.g. communications exchange equipment) far outweighs the economic value of the air-conditioning units themselves (this applies equally to many commercial uses for air-conditioning). Even if damage occurred to the units in the long term it would be more economic to continue to run them if they were able to keep functioning, rather than risking damage to more expensive equipment.
- Previous testing of computer cooling fan and domestic cooling fan bearings found that these bearings functioned far better than expected in an ash laden environment, and continued to work after 720 hours of testing (Gordon et al., 2005). This suggests that at least medium-term impacts on air-conditioner fans are unlikely

- Given the short duration of most ashfalls, it is unlikely that there would be a need to operate air-conditioning units under such conditions for a longer than a few hours or days. Continuous ashfall for longer periods is of course possible, but a sustained eruption and near continuous ashfall will likely result in power cuts, and evacuations leading to a lack of a need for air conditioning.

In order to test the performance of air-conditioning units in ashfall conditions it was necessary to build a suitable apparatus for testing, and to run the units without ash to establish a baseline. As temperature was being measured, a stable environment with little or no change in ambient temperature was also needed. This was found in the basement of the Department of Geological Sciences at the University of Canterbury, which has one small entrance approximately 80 metres from the area used for testing, and is well insulated from outside temperature fluctuations.

Eliminating external influences on air temperature meant that any change had to come from the unit itself, which remained at a relatively constant temperature (fluctuations $<0.3^{O}C$) under normal circumstances. Therefore once ash was added to the atmosphere around the intakes it would be possible to record any change in performance due to ashfall.

3.5.2 Testing methodology

3.5.2.1 Ash type

Several cubic litres of fine volcanic ash were required to perform this testing. The tests were intended to simulate a distal ashfall. However access to fresh volcanic ash was problematic, given the lack of recent (magmatic) eruptions in New Zealand. As any fine ash from the most recent magmatic eruption New Zealand has experienced (1996 Ruapehu) has long since been washed away by rainfall, and ash from recent overseas eruptions is both expensive to obtain and subject to Ministry of Agriculture and Fisheries (MAF) restrictions, it was necessary to create an artificial ash that would behave in the same manner that fresh ash would. To do this, unweathered samples of basalt were taken from the Lyttelton Volcano on Banks Peninsula, Canterbury. These samples were broken down in size, before being crushed in a '*Rocklabs Boyd Double Action Jaw Crusher'*. This produced an ash-like material, but the grainsize was extremely varied, with some particles up to 2 mm in diameter. These samples were passed through a 250 µm sieve to remove coarse particles. The resulting rock flour or 'ash' was analysed for grainsize in a Micromeretics Saturn Digisizer 5200. Results indicated a modal grainsize of 100.2 µm and a mean grainsize of 93.86 µm. Further analysis was conducted by photographing the 'ash' with a scanning electron microscope. Grain shape was compared with samples of ash taken from several different eruptions. These included fresh basaltic ash collected during the 2002 eruption of Mount Etna, Italy, andesitic ash from the 1996 eruption of Ruapehu, New Zealand and the 2007 eruption of Merapi, Indonesia. The shape of the grains was of particular importance, as this would influence how well the grains adhered to surfaces. Figure 3.2 shows the comparisons between these 3 types of ash and crushed Port Hills basalt.

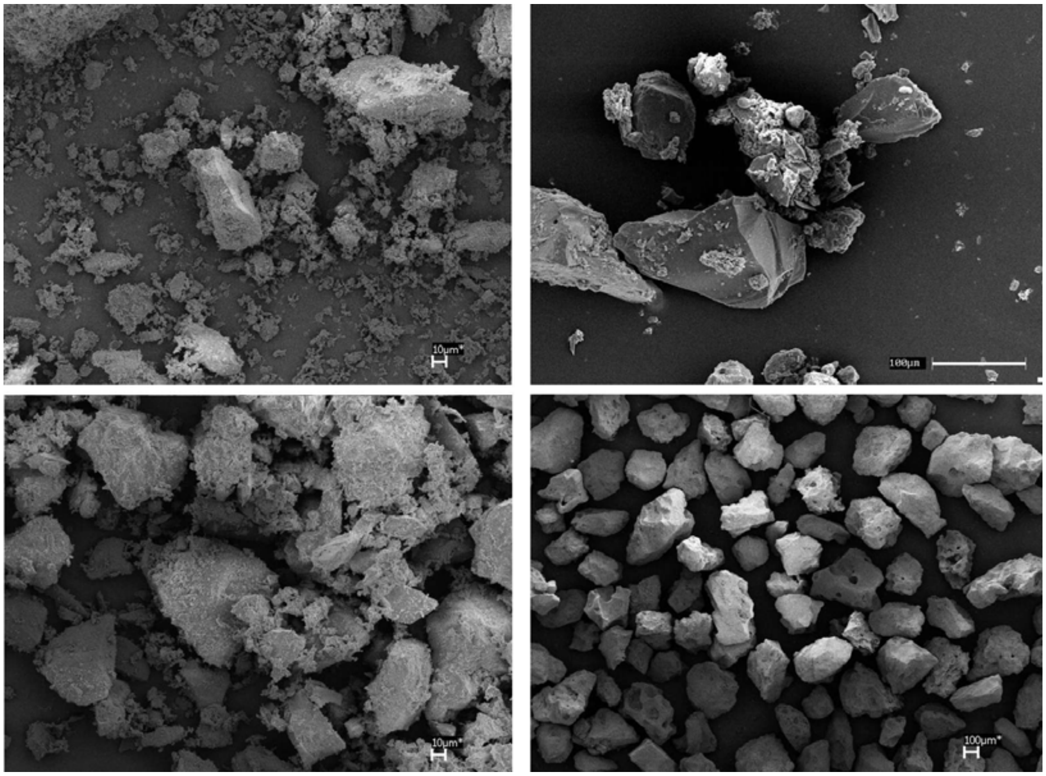

Figure 3.2 Clockwise from top left: Crushed Port hills basalt, Glassy basalt from Etna 2002, Ruapehu 1996 andesite (no fines), Merapi 2007 andesite.

A good correlation in grain shape was found between the 1996 Ruapehu ash, the 2007 Merapi ash and the crushed Port Hills basalt sample. The predominance of glass (tachylite) in the fresh basalt sample from Etna compared to the higher crystal content of the other samples meant that this sample was slightly more angular. However the crushed basalt samples were felt to be a similar enough shape to actual ash samples to be used as a proxy for this type of testing.

As well as determining how ash adheres to surfaces, grain shape is an important factor in determining the abrasiveness of the ash, as is the composition. While volcanic ash containing quartz (e.g. andesitic or rhyolitic ash) would be slightly more abrasive, this was not considered to be necessary for testing the short term use of air-conditioners in ashfall situations. Potential differences caused by this were not thought to be significant for the purposes of this experiment, since the objectives were to determine the adherence of ash to the condenser, and how any blockages created would affect air-conditioner performance, rather than the long term durability of air-conditioning units during ashfall.

3.5.2.2 Unit types

Through-wall or window unit type

Initial tests were conducted on a Mitsubishi electric MWH 17KV room air-conditioning unit supplied by Telecom New Zealand. This unit had been taken out of a local exchange in order to upgrade to a newer unit, but was still in good working order. The MWH 17KV is fully self-contained in a steel casing which houses 2 radiators, one facing the inside of the building and one outside. The unit is mounted in a wall cavity or window; they are often referred to as a window unit or window rattler. Either radiator can be used as a condenser or an evaporator as required, meaning it is capable of both heating and cooling. It has a cooling capacity of 4.98 KW and a heating capacity of 5.42 KW. For the purposes of this testing the unit was set to run at maximum capacity. Air entering the unit from the outside was drawn into the unit through a metal grill using a large fan, which then pushed the air through the radiator (condenser) to the outside again. This differs from a conventional split system unit in that air is pushed outwards through the radiator, rather than being sucked inwards through the radiator before exiting out the front of the unit. The exterior side radiator is used as a condenser when the unit is used to cool air, and as an evaporator when warm air is required inside. The exterior radiator fins are closely spaced at 1.5 mm apart.

No outside air is brought inside with heat exchange units, this includes through wall units. The MWH 17KV is divided down the centre, with the only connections between the two halves being the pipes through which the refrigerant moves to enable the heat exchange, and a prop shaft which connects and turns both fans (the same motor thus powering both fans). Interior air is drawn into the unit through the radiator (evaporator when cooling) and blown out again in the same manner, cooling the interior of the building (figures 3.3 & 3.4).

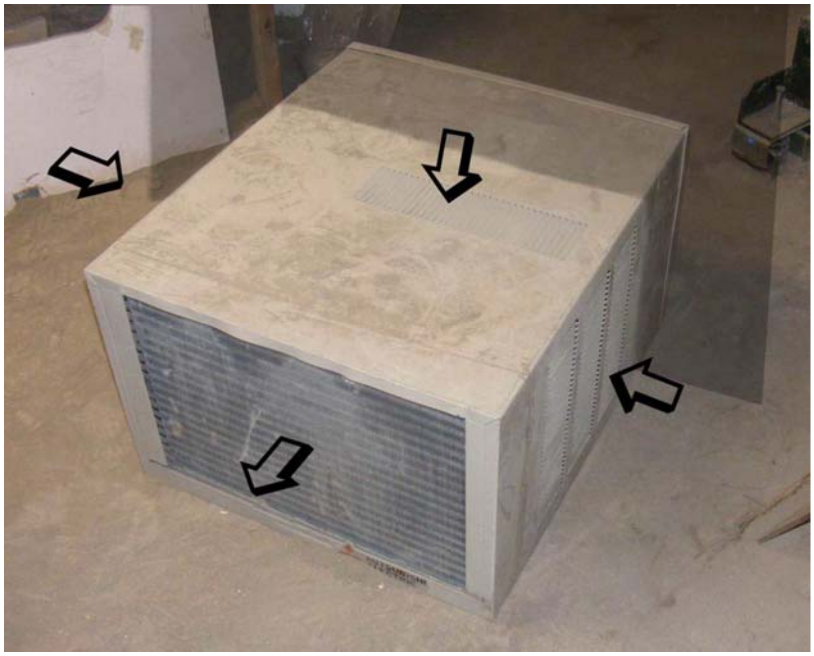

Figure 3.3 Mitsubishi MWH 17KV exterior side. Arrows indicate air direction, the shaded area indicates where the building wall or window would normally be

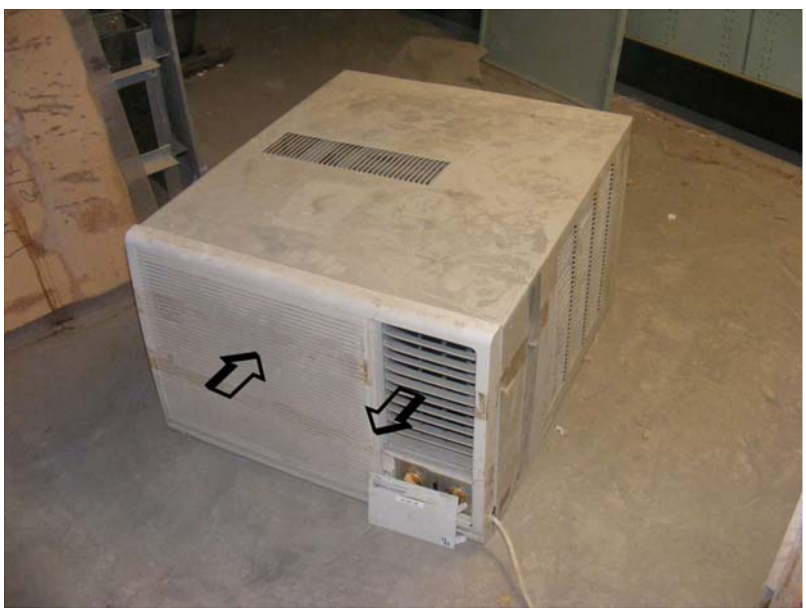

Figure 3.4 Mitsubishi MWH 17KV interior side. Arrows indicate air direction

Split system type

The second unit tested was a Toshiba RAV-200KH split system unit, one of Toshiba's light commercial range of air conditioners (figure 3.5). This unit was taken from an urban telephone exchange in Christchurch as part of a general maintenance program. Units are retired after a few years even when working well; this unit was in perfect working order. It has a cooling capacity of 5.8KW, slightly higher than the first unit tested. Being a split system this air conditioner consists of two sections; an outside unit and an inside unit. These are connected by pipes carrying refrigerant. During testing the inside unit was not subjected to any ash, and ran as it would under normal circumstances, sucking air from the room through an evaporator with a fan, and blowing the cooled air out again into the room. The outside unit drew air through the condenser via a large fan, which pushed air out of the reverse side of the unit. This type of unit is found worldwide in a variety of applications. It is also typical of those used by Telecom in both exchange buildings and cell tower exchanges all over New Zealand. Fin spacing in the condenser is 2 mm. For the purposes of testing the thermostat was repositioned on the outside of the air-conditioner where it would remain at room temperature, ensuring the unit continued to operate at maximum capacity for the duration of the testing.

Figure 3.5: Internal and external sections of Toshiba RAV-200 split system pre testing

3.5.3 Testing – Mitsubishi electric air conditioning unit

3.5.3.1 Test set-up

In order to simulate ashfall and measure performance it was necessary to create an environment where the air intakes and outputs for both the condenser (exterior) side and the evaporator (interior) were kept separate. It was also desirable to prevent too much ash from being distributed around the testing area. Not only would this create a mess but could affect the results of the test if ash were to also be drawn in to the interior intake of the air conditioning unit.

The experimental set-up consisted of a large wooden box built around the air-conditioning unit and divided up into four sections, separating interior/exterior air, and intake/output air. This prevented air being recycled through the system immediately after exiting it and thus potentially altering temperature – an initial test run in a prototype test unit did not separate intake and output air adequately. This resulted in air being recycled, on both sides, so that temperatures became hotter and colder respectively until the cold side iced up at -11^{O}C, the hot air reached over 85^{O}C before being manually shutdown.

Air moving through the exterior section of the system would be carrying any ash which had not lodged within the unit. To prevent large quantities of this ash entering the testing area and eventually being redrawn into the air-conditioner, a filter was used instead of an end wall in the test box. This also allowed air to freely leave the test box. This was necessary as the intake and output areas were separated, a solid box with a separation between the air intakes and output side would leave the air with nowhere to go, resulting in the creation of backpressure, which would in turn prevent air being drawn into the unit in the normal manner. Figure 3.6 illustrates the setup of this experiment.

Figure 3.6: Left: Interior air side of MWH 17KV air-conditioner with intake and outlet separated to monitor temperature. Centre: looking down on the unit, ash was introduced in this central area. Right: the filter covering the exit for the exterior air

The filter used was EU3 media, as used by Telecom in the fresh air intakes on urban exchanges. This type of filter is designed to remove coarse particulate matter, but below 100 microns performance drops off; 80% of particles at 10 microns will be caught, 45% of particles at 1 micron. This would not only stop (some of) the ash from escaping into the room, but give an indication of the effectiveness of such filters in an ashfall. Regular cleaning of this filter was undertaken to prevent blockages from slowing output air and affecting the performance of the air-conditioning unit. The top of this part of the unit was covered in a Perspex sheet to prevent ash escape but leave the interior visible. The input area of the unit was uncovered, to allow ash to land on the unit. The divider between it and the interior part was positioned as a wall or window would be under ordinary installation of this type of air-conditioner. The area of this section measured 430 mm x 1160 mm, giving a surface area of $0.499m^2$. This equates to the approximate area affected by the airflow created by the unit. 100 ml of ash by volume therefore equated to a thickness of ash of ~ 2 mm. Similar divisions were employed on the interior (evaporator) side, without the need for filtration. All dividers were sealed to prevent ash or air of a different temperature affecting results. Exterior air (ambient air) was continuously monitored with a room thermometer, the performance of the air-conditioning unit was continuously monitored with a cyberscan pH/temperature meter positioned 5 cm in front of the interior air outlet. Airspeed was monitored outside the condenser pre testing, with 15 readings taken in a grid pattern in front of the unit. These values average out at 10.6 km/h.

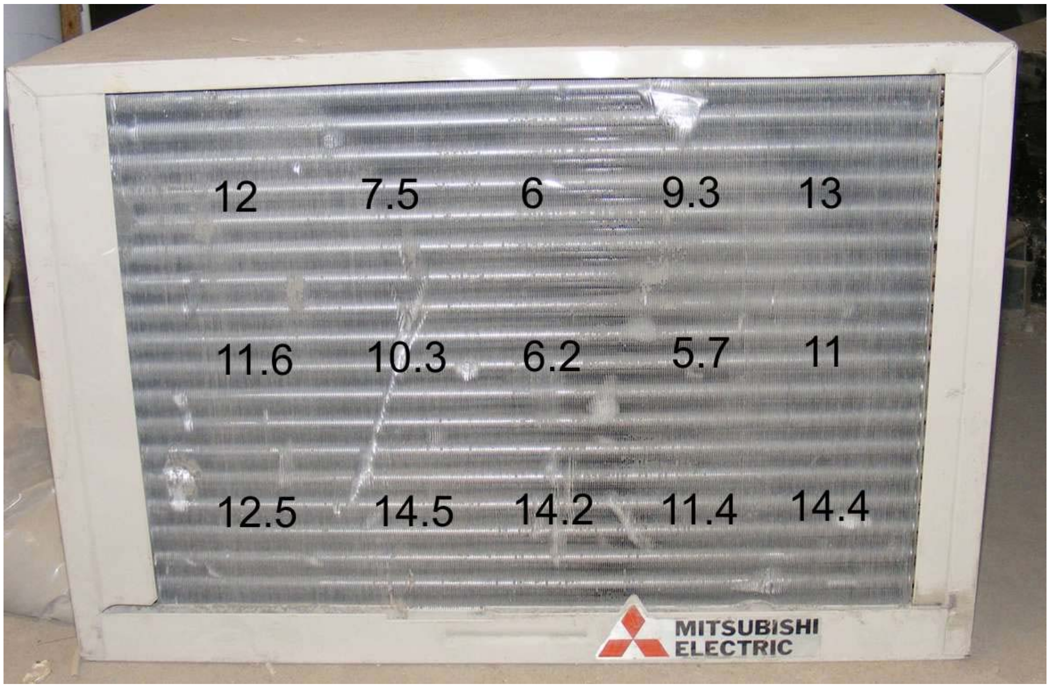

Figure 3.7: Airspeed (km/h) outside the exterior condenser prior to testing

3.5.3.2 Testing

Each period of testing was preceded by turning on the air-conditioning unit 1 hour beforehand. This ensured that the unit was running efficiently, that it was adequately ‘warmed up’ and that the temperature in the room was stable. All air to pass through the unit air was directed away from the intakes so that the cool air from the evaporator and hot air from the condenser mixed sufficiently to reach equilibrium and not alter the ambient room temperature. Room temperature was regularly checked throughout the course of the experiments, and on all but one occasion remained constant at 25.7^{O}C. On that occasion other machinery in the same room was in use, which may explain the slight rise. The unit was run for 12 hours pre-testing, and output temperature monitored. This established a baseline for the output of the machine. Cold air temperature fluctuated up to 0.3^{O}C either side of 10.4^{O}C, but usually stayed within 0.2^{O}C of that temperature. It was noticed that moving the thermometer gave differing results of up to 1^{O}C even with slight movements, consequently it was attached to a wooden post in front of the airflow. When used to heat air, the output of 53.5^{O}C fluctuated a little more, up to 1 degree either side of this value.

To introduce ash to the unit, an amount (initially 100ml) of dry ash was sprinkled over the air intake for the outside of the air-conditioner. The best method for doing this was found to be by shaking a sieve (250 µm) at a height of about one metre above the unit. This was high enough to allow ash to disperse, and low enough to ensure it all landed on the intake area. The sieve was sufficiently moved around to ensure the consistent application of ash over the whole area. No secondary fan was required to help introduce or remobilise ash as the unit provided enough air movement itself. Furthermore it was desirable to as closely mirror a real ashfall as possible, rather than making all of the ash in the area remobilise and enter the unit.

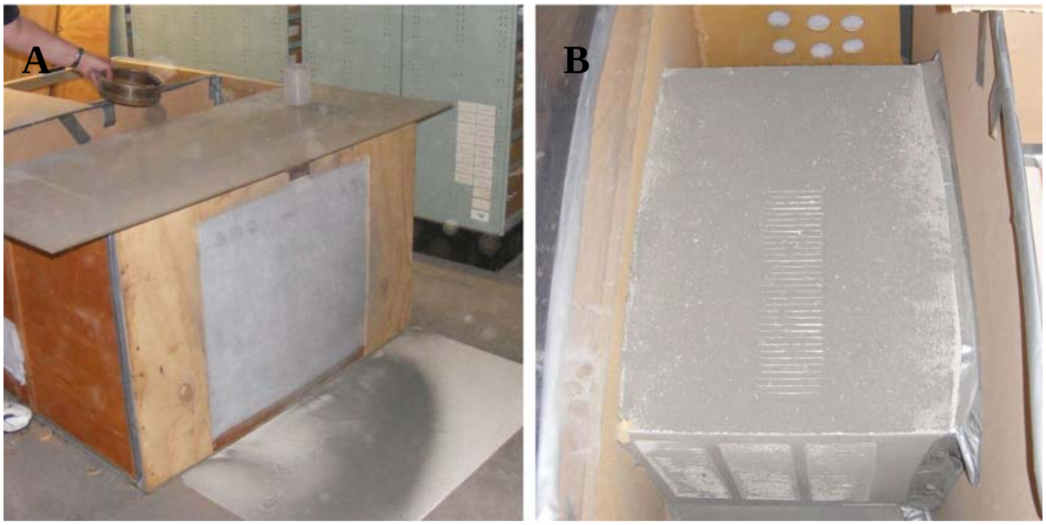

Figure 3.8: A. Introducing ash using a sieve, note the ash on the white board that has passed through the filter. B. the unit after ~ 2 mm of simulated ashfall

The specified amounts of ash (see results table, appendix 1) were sprinkled over a 5 minute period with a 5 minute break every 30 minutes. This allowed other small tasks to be achieved - such as cleaning the filter, checking equipment, refilling water bottles (wet testing). At 500 ml per 30 minutes, the amount of ash introduced equated to an ash accumulation rate of 2 mm (un-compacted) per hour. This was felt to be a realistic representation of an actual fallout rate for a distal area. Actual fallout rates vary immensely between eruptions, ranging from millimetres or less over days or weeks (e.g. Etna, 2002), to metres in a matter of hours for some proximal events (e.g. Tarawera, 1896 (Keam, 1988)). Water was added in the wet testing by spraying a mist of water droplets from below the sieve that was sprinkling ash. This was added continuously while ash was being distributed, at a water to ash ratio of 2:1 (by volume). Water temperature was 25^{O} C

The filter at the end of the test box was cleaned at least every 30 minutes to allow air to freely exit, and prevent back pressure building up. This was done by vacuuming the filter, which worked effectively.

3.5.4 Results

3.5.4.1 Air conditioner performance in dry conditions

The performance of the MWH 17KV was better than anticipated. Initial tests continued until the unit was subjected to a 2.6 mm thickness of ash. This took 75 minutes. During this time the output temperature rose from 10.2^{O}C to 10.6^{O}C and back to 10.4^{O}C (results are listed in appendix 1). These temperatures were all within the normal fluctuations. At this stage the unit was gently removed from its casing (it slides out on tracks), inspected and replaced. Very little ash was visible inside the radiator, trace amounts adhered to pipes and the compressor inside the unit.

Testing resumed after the unit ran for 60 minutes to ensure it had worked up to maximum performance and come down to temperature. Ash addition continued until a 4 mm thickness of ash was reached, the unit was again inspected (figure 3.9)

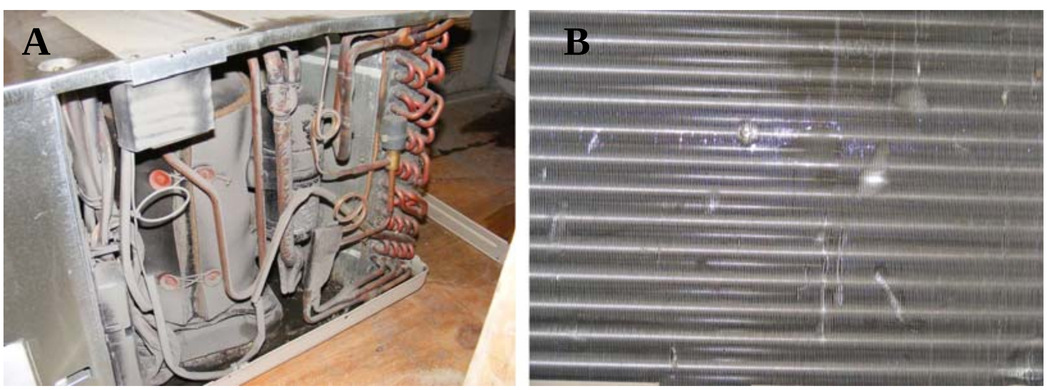

Figure 3.9: A. The interior of the unit after 4 mm of ashfall, B. The condenser after 4 mm of ashfall, showing no adherence of ash to the fins.

Slightly more ash was caught inside the unit on internal components, but no blockage or lodged ash was visible in the condenser. Testing continued again until the unit had been subjected to a 6 mm thick ashfall, over a 3 hour period. Temperatures had remained stable at 10.4^{O}C 10.6^{O}C during this period. At this time the rate of ashfall was increased slightly from 2 mm per hour to 2.5 mm per hour. Ash addition continued until the air conditioner had been subject to a 10 mm covering of ash, over a 275 minute period. Output temperature was not further affected, remaining at between 10.4^{O}C and 10.6^{O}C. The unit was left running for another 3 hours, but no further change occurred. Inspection revealed a covering of ash inside the base of the unit of up to 2 mm, but only trace amounts of ash appeared within the condenser. Figure 3.10 illustrates temperature vs. ash thickness.

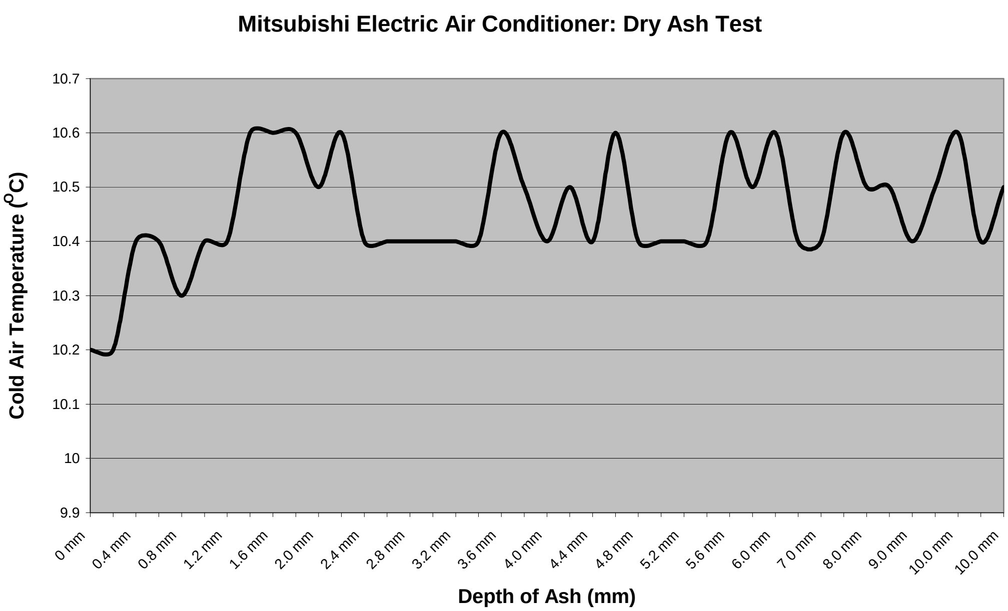

Figure 3.10: Temperature vs. ash thickness for dry ash test.

Although there was a slight initial rise in temperature there was no evidence of a drop off in performance of the air-conditioning unit. Temperature remained within normal limits, as established pre-testing. Interior airflow remained the same as the fan continued to operate at the same speed, and the temperature remained within normal operating levels. Ash did not appear to lodge within the radiator, although it was building up inside the unit. Eventually this could cause problems if ashfall continued, potentially causing the fan motor or compressor to overheat as a thick covering of ash insulated the internal components.

3.5.4.2 Air conditioner performance in wet conditions

Testing initially simulated a very light ashfall of up to 1 mm thickness. Temperature was not affected by this amount of ash, though trace amounts adhered to the condenser. The peak of 10.7^{O}C after 1 mm of ash (figure 3.11) is still within the limits of usual temperature fluctuation. Testing resumed the next day, but output temperature had dropped by 0.6^{O}C to 10.1^{O}C, again within normal limits. Simulated ashfall continued until the unit had experienced 5 mm of ash. Small amounts did adhere to the unit, (figure 3.12) but not enough to cause any impacts on unit performance. Figure 3.11 illustrates temperature vs. ash thickness. This test simulated a brief, light ashfall lasting 2.5 hours.

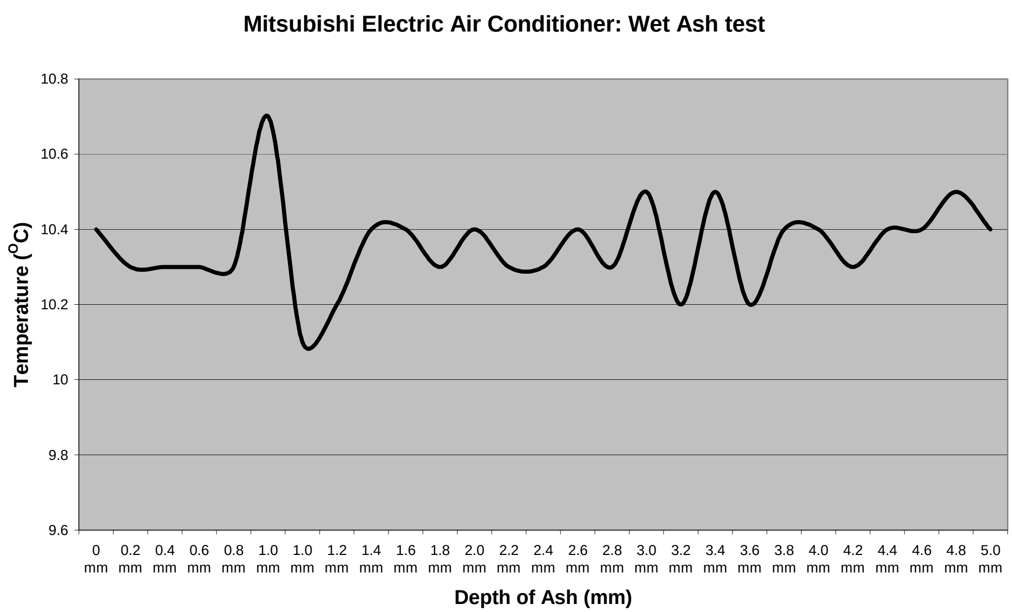

Figure 3.11: Temperature vs. ash thickness for wet ash test.

Figure 3.12: Condenser after 5 mm of wet ash. Note small amounts of ash adherence

3.5.4.3 Air Conditioner performance when heating

In order to test whether ash was cleared from the condenser due to it being hot, drying any moisture that may have helped the ash to adhere, it was decided to run a test with the unit in reverse. In this way the air-conditioner would be acting as a heat pump, and the exterior radiator would be acting as an evaporator. As the evaporator was cold and wet, it was thought that blockages would be more likely to occur in the radiator as ash clogged up the gaps between the fins. Again tests simulating 5 mm of ashfall were conducted. The results indicated that performance was not affected either wet or dry ash tests. Fluctuations in temperature stayed within normal operating limits. A slight increase in the amount of ash adhering to the condenser was seen in both the wet and dry ash tests, compared to the tests using the unit for cooling. Whether the ash was wet or dry did not affect results, as when the radiator acts as an evaporator, its cold surface is already wet.

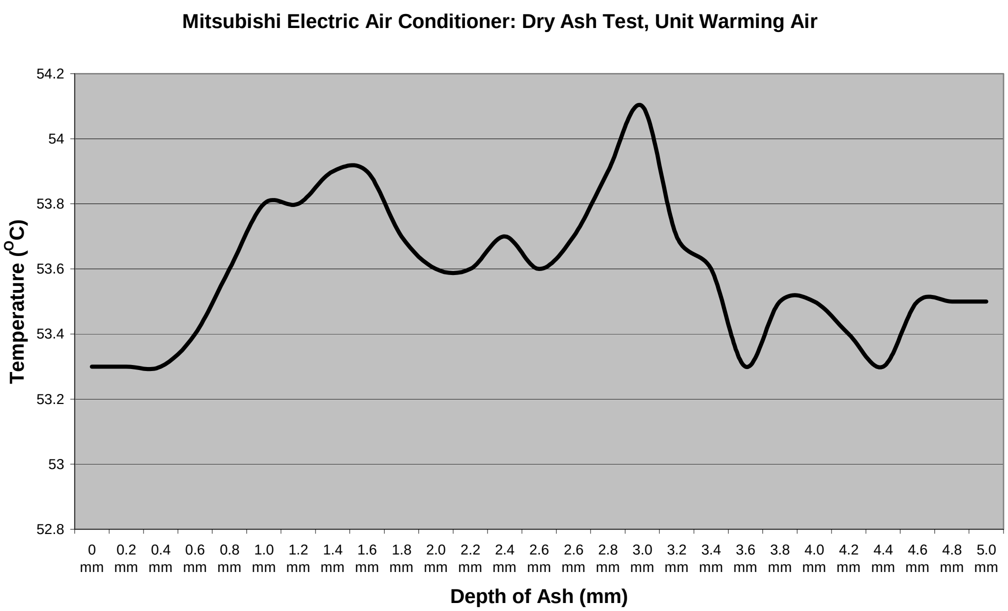

Figure 3.13: Temperature vs. ash thickness for dry ash test, heating air

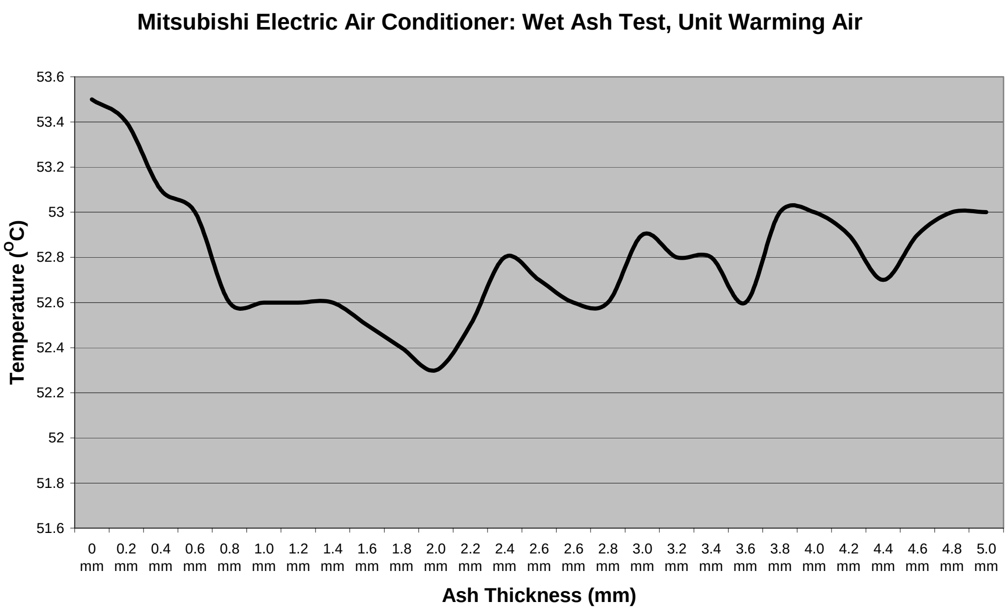

Figure 3.14: Temperature vs. ash thickness for wet ash test, heating air

3.5.5 Testing – Toshiba air conditioning unit

3.5.5.1 Test set up.

The setup for the testing of the Toshiba unit followed the same principles as those used in the testing of the Mitsubishi air conditioner. A large box with a filter in the end wall was constructed to house the exterior part of the unit. A divider separated the back and front parts of the unit, to prevent the air that was being drawn into and blown out of the unit from mixing. This could result in temperature fluctuations. The top of the intake area was left open so that ashfall could be simulated, the outlet on the exterior side was lidded to keep the ash from entering the room where it would be entrained in the inside part of the unit (figure 3.15).

Figure 3.15 Toshiba unit test setup. Ash was introduced behind the external unit (to the right in this photo). Ash and air moved through the unit from the right of this photograph to the left. The internal part of the system drew air in through the intake facing the camera, and out to the left after mixing with air from the external part, thereby maintaining constant ambient temperature.

The intake area was constructed to allow a similar amount of air to enter the unit as would under “normal outdoor” conditions. These conditions are problematic to determine, as unit setup can vary immensely. Exterior units may be positioned with the intake within a few centimetres of a wall, mounted on roofs with unobstructed intakes, or even inside cell tower exchanges with the intake facing the inside of the exchange. The total area affected by airflow created by the units can therefore vary immensely. For the purposes of this testing an unobstructed intake and a lack of wind (ash falling vertically) were assumed. In this situation the area affected by the exterior unit fan was found to extend to approximately 350 mm beyond the unit casing. This was tested by observing small amounts of ash dropped from above the unit pre-testing. Any ash falling outside this range did not enter the unit. This value is to be taken lightly; variables influencing the area around units that ash may enter from include the different unit configurations mentioned above, wind speed and direction, settling velocity of the ash, ash grainsize and fan speed on differing units. A slightly larger area was created behind the unit, extending beyond this to 370 mm from the casing. To the side which is also used as an air intake through the condenser, the box wall was located 150 mm beyond the casing, as air entering from the side does so at a lower velocity, and a smaller area was affected. Holes were cut in the wooden box sides to allow air to circulate more freely.

Mounted outside this box was the interior part of the unit, cooling ambient air. Refrigerant was connected through pipes passing through the side wall. Air from this part of the system was directed towards and mixed with the air coming out of the exterior part of the unit. In this way the ambient air temperature remained in equilibrium, with very little change occurring during the course of the experiments. Ambient temperature during this testing was less than during the testing of the Mitsubishi electric unit, typically 21.7 to 22.1^{O}C. Some fluctuations were experienced outside these values, but appeared to have no effect on the cold air output. A small hole was drilled in the side below the cold air output, in which a thermometer was positioned to monitor the cold air temperature. This ensured that the thermometer could not move in relation to airflow, potentially affecting measurements.

To establish how much ash may affect air conditioner performance it was necessary to know the amount of ashfall the unit was subjected to. This was determined by calculating the surface area around the unit from which ash could potentially enter the intake. When a known volume of ash fell over this area, an equivalent depth of ashfall could be calculated. In this case, the intake area of the unit measured 880 mm wide and 310 mm deep on the unit's side. Adding the area around the unit that ash could potentially be entrained from gave a surface area of 1030 x 660 mm. Once the area taken up by the unit itself (880 mm x 310 mm) was subtracted, a surface area of 407000 mm^2 remained. This meant that 407 ml of uncompacted ash, sprinkled evenly over this space would equal a 1 mm covering of ash (uncompacted) on the ground. For testing purposes this was rounded to 400 ml.

Airspeed at the entrance to the condenser on the outside of the unit was also measured. As the unit condenser extended beyond the dimensions of the diameter of the fan, and curved around the side of the fan on one side, airspeed would naturally differ considerably depending on where measurements were taken. 70 measurements were taken, spread over a grid over the back and side of the exterior condenser. Results are given in figure 3.16.

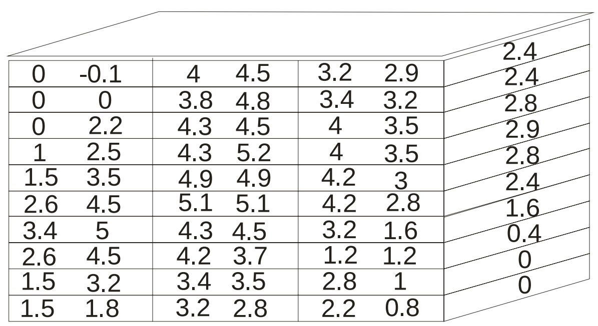

Figure 3.16: Airflow in km/h at the outside of the exterior condenser pre testing. Negative values indicate air being blown outwards rather than sucked inwards.

Air speeds in this unit were significantly lower than in the Mitsubishi unit. Larger units tend to have larger but slower (and quieter) fans. Average air speed over the entire unit pre-testing was found to be 2.5 km/h. The fastest, near the centre of the fan was 5.2 km/h. Areas of "dead air' where no movement was detected were present in opposite corners of the unit.

3.5.5.2 Testing

Testing of the Toshiba RAV-200KH air-conditioning unit followed similar procedures to the Mitsubishi air conditioner. Each period of testing was preceded by running the system for at least 60 minutes to ensure the system was operating at maximum efficiency. Ash was sprinkled at intervals above the intake for the exterior part of the unit, in the same way as described in section 3.5.3.2., using a 250 µm sieve. As with the Mitsubishi tests, the filter in the end of the test box was regularly vacuumed to prevent blockages causing a build up of pressure in front of the unit, which would in turn reduce air intake.

Testing began with a simulated light dry ashfall, of 3 mm per hour. To achieve this 100 ml of ash was distributed over the exterior area every 5 minutes. This continued until over 22 mm of ash had accumulated. As this testing took place over a few days there were times when the unit was running in order to warm up and reach maximum efficiency, before ash was again added. Total operating time when the unit had been subjected to an equivalent ashfall of 22 mm was therefore 660 minutes, rather than 440 minutes. This was not seen to be problematic, as the rate of ashfall need not be consistent in actual volcanic eruptions, yet air-conditioning units are likely to continue operating as much as possible.

An increase in ashfall rate was simulated after this, as 300 ml was introduced every 5 minutes, (9 mm per hour) until a 35 mm thickness of ash was reached. At this point the ashfall rate was increased again to 500 ml or 15 mm per hour, as the previous increase in rate of ashfall did not appear to affect the results in terms of temperature changes. Testing for the dry ash test ceased after 1350 minutes of testing, and a simulated ashfall exceeding 95 mm in thickness.

The radiator was carefully cleaned using compressed air, a vacuum cleaner and a brush prior to beginning the wet testing. The testing of ashfall in wet conditions followed the same procedures as with the testing of the Mitsubishi unit. The main difference was the ratio of ash to water, at 10:3. Water temperature was 22^{O}C for these tests, matching average ambient room temperature. Since results from the dry testing indicated ashfall rate did not appear to have much bearing on results, 500 ml of ash was added every 5 minutes from the beginning of testing, (15 mm per hour) rather than starting with a smaller amount. Testing in wet conditions continued until the unit had been subject to the same amount of ash as it was in the dry testing; a 95 mm thickness.

3.5.6 Results

3.5.6.1 Air conditioner performance in dry conditions

The results of the Toshiba test were significantly different to the Mitsubishi electric testing. An effect on the output of the system was almost immediately apparent. After only 2 mm of ash was deposited, temperatures had risen from an initial 10.3^{O}C to 11^{O}C. They climbed as high as 11.5^{O}C, but dropped to 11^{O}C before the end of testing on day one, at 185 minutes or 9 mm of ash. Figure 3.17 illustrates temperature vs. thickness of ashfall over a 24 hour period.

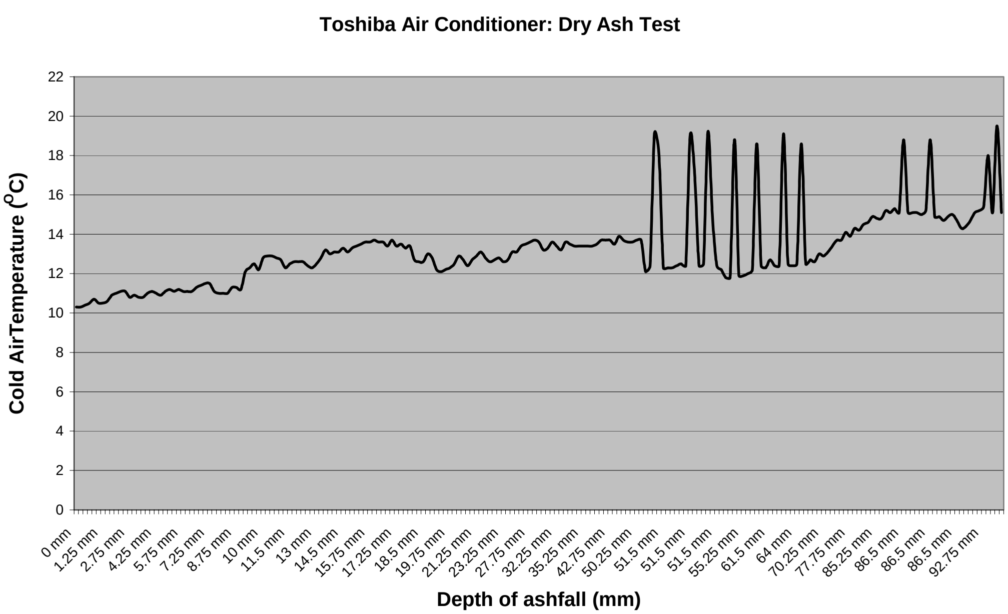

Figure 3.17: Cold air temperature vs. ash thickness for dry ash test (Toshiba). Peaks in temperature are associated with exterior unit shutdowns.

Photographs taken at this time show ash lodged within the unit, resting between condenser fins, supported by the horizontal coils (figure 3.18). It is thought that the ash caused an insulating effect on the condenser, preventing heat from escaping. This is because although temperatures had risen and some ash was present within the condenser, there was not enough to cause any significant blockage to airflow.

Figure 3.18: Exterior unit condenser after 9 mm of ashfall. Note ash accumulating on horizontal coils

The following day the unit was started 60 minutes before testing. After this warm up period output temperatures had climbed to 12.1^{O}C, in response to the ash present in the condenser. Although this temperature is higher than those experienced at the close of testing on the previous day it follows the general trend of gradual warming shown in figure 3.17. Ambient temperature was exactly the same, so this was not contributory.

Further temperature rises continued as more ash was added to the system, From an initial temperature of 12.1^{O}C a the start of the day, output temperature rose to a maximum of 13.3^{O}C, by the time 15 mm of ash (total) was reached, after a total running time of 370 minutes. The next break in testing did not result in any change in output temperatures after testing resumed. During the next hour another 3 mm of ashfall was added, temperatures remained between 13.4^{O}C and 13.7^{O}C. At this stage the top of the unit was briefly removed to inspect the interior. While some ash was present in the condenser, very little had remained in the base of the unit, as the airflow created by the fan had removed all but a thin covering of ash, bare metal was still visible on the base. Although this inspection involved stopping the unit for only 5 minutes, upon resumption of testing colder air was again produced by the air conditioner, dropping by 0.7^{O}C from it's previous output to 12.6^{O}C. This is likely to be due to small amounts of ash being dislodged from the condenser as the lid was removed and replaced, as well as giving the compressor a chance to cool slightly while being shut down. Temperature rose to 13^{O}C after being subjected to another millimetre of ashfall, the total amount now 19 mm. Figure 3.19 illustrates ash lodging in the condenser after 18 mm of ash

Figure 3.19: Condenser accumulating ash after 18 mm of ashfall

Testing the following day again began with a lower temperature output, of 12.2^{O}C. Internal components within the unit – such as the compressor, had cooled overnight, and had not yet started to overheat, despite the unit being given 60 minutes to run prior to testing. By this time visibly less ash was being drawn into the condenser as blockages began to affect the airflow. In some areas it could be seen being blown back out of the condenser. Once again temperature began to rise as ash was added. By the time the increase in ashfall rate occurred after 660 minutes of testing, temperatures were once again up to almost 13^{O}C. These slowly rose as more and more ash caused blockages in the condenser to increase. Temperatures remained over 13^{O}C but under 14^{O}C until the end of testing for the day, at 820 minutes and over 51 mm of ashfall (figure 3.20). By now the rate of simulated ashfall was at 15 mm per hour.

Figure 3.20: Condenser after 51 mm of ash

Although the condenser was significantly blocked with ash, when the unit was restarted the following day, output temperatures again reached as low as 12.1^{O}C. However this did not last for long, as 70 minutes after being switched on, and before more ash was even added the exterior unit shut itself down. This was due to the high pressure switch being tripped in the compressor. This occurs in response to an excess of heat in the condensing unit, in turn causing higher pressures in the compressor, making the compressor work harder to maintain lower temperatures. As less heat is transferred to the outside air, more heat remains inside the condensing unit (including the compressor) and the refrigerant. This causes the pressure to rise inside the compressor, until the high pressure switch trips, shutting down the unit. Some air conditioners will not then restart until manually switched off, then on again. This unit automatically switched itself on again after temperatures had cooled sufficiently. In this instance it took 5 minutes to do so. During that time the interior fan continued to function, but air was not being cooled effectively, and output temperature rose to 19.1^{O}C within 2 minutes, remaining at that temperature for the duration of the exterior unit shutdown. Once the exterior fan switched on again, temperatures took 3 minutes to return to previous levels.

No ash was added for the next 2 hours, to monitor how the unit would run. During this time two more 4 minute shutdowns occurred, as the compressor again over pressurized.

When testing resumed the following day, ash was again added, resulting in a 2 minute shutdown. Compressor and exterior fan shutdowns of between 2 and 5 minutes began to occur every 20 to 30 minutes, output temperatures remaining between 12^{O}C and

13^{O}C, aside from when the compressor had shut down. This slightly lower temperature than the previous highs over 13^{O}C was due to the condenser and compressor cooling during the shutdown periods. Air flow was measured again at this point, and was found to have been drastically reduced (figure 3.21).

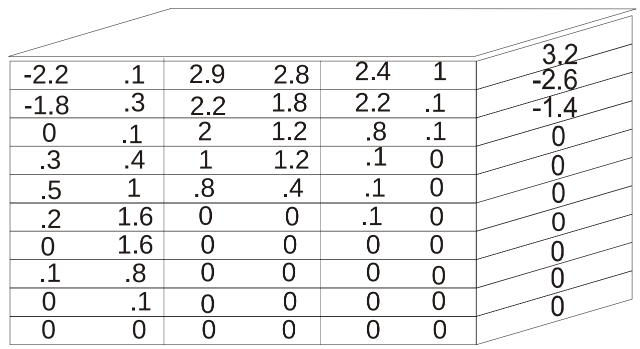

Figure 3.21: Airflow in km/h at the outside of the exterior condenser after 1115 minutes of testing (system subject to a total depth of 64 mm of ash). Negative values indicate air being blown outwards rather than sucked inwards.

The pattern of shutdowns every 20 to 30 minutes changed after 1125 minutes of testing, and over 65 mm of ash. Over the next 110 minutes a further 21 mm of ash was added, the compressor stopped shutting down, but cold air temperature began to rise, reaching 15.3^{O}C before the compressor shut down for two minutes again. Two more 2 minute shutdowns occurred in the next 90 minutes, then the unit began to function for only 5 minutes or less between the compressor stoppages. After a total of 1350 minutes, and a simulated ashfall of just over 90 minutes the entire system shutdown, and the display registered a malfunction code. This code (21) indicated a failure of the high pressure switch to reset. This required a manual restart, though would have happened soon again had it been restarted without cleaning out the condenser. Testing ceased at this point as the unit had effectively failed under these conditions.

3.5.6.2 Air conditioner performance in wet conditions

Although the unit was cleaned prior to testing, initial cold air output temperatures before the addition of ash were not as low as those achieved prior to dry testing, but approximately 1^{O}C warmer. This could be because of two things:

- The compressor had suffered damage due to prolonged high pressure leading to repeated shutdowns
- A small amount of coolant had leaked from the unit due to the prolonged high pressure during the later stages of the dry test

Results from this testing followed a similar pattern to the dry testing. An increase in temperature was seen almost immediately after ash began to be added (figure 3.22). The first 280 minutes of ashfall equated to a depth of 32.5 mm of ash, and resulted in a gradual temperature rise from 11.3^{O}C to 13.6^{O}C. Ash adherence differed to the dry testing, in that ash preferentially stuck to the outside of the condenser and it's protective grill, as well as lodging within the radiator (figures 3.23, 3.25& 3.26).

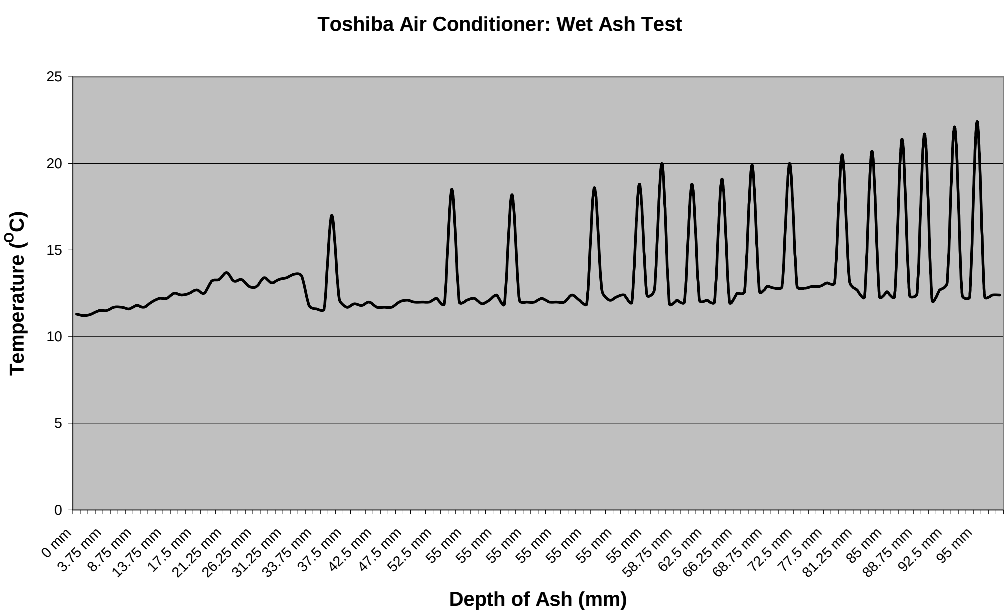

Figure 3.22: Cold air temperature vs. ash thickness for wet ash test (Toshiba). Peaks in temperature are associated with exterior unit shutdowns.

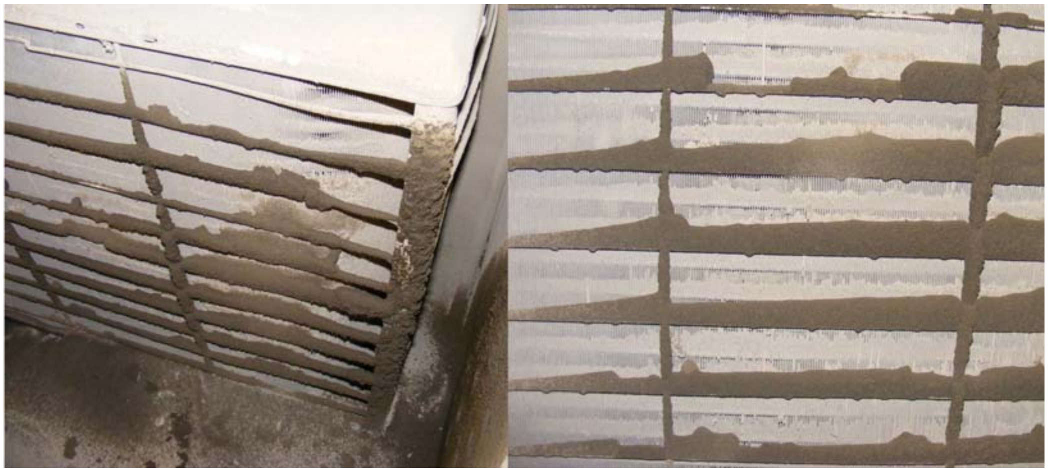

Figure 3.23: Condenser after ~32 mm of ash. Note the adherence of ash to the outer grill

The condenser and compressor had cooled by the time testing resumed the next day. Initial temperatures stabilised at 11.8^{O}C once the system had run for 60 minutes. A further litre of ash and 300 ml of water were added before the air conditioner had its first compressor overload and corresponding shutdown of the exterior unit, for 2 minutes and 30 seconds, after a total depth of ashfall of 35 mm. This is visible as the first sharp peak in figure 3.22. Ash continued to accumulate on the condenser, but temperatures remained fairly constant at 12± 0.3^{O}C. 75 minutes and 19 mm of ashfall later the second compressor overload and shutdown occurred, this time lasting for over 4 minutes. No further ash was added for the next 2 hours to ascertain whether or not the fan could clear any ash from the condenser. It did not appear to, and 3 more compressor and fan shutdowns occurred in this time.

By now the unit had been running for 10 hours and had been subjected to 55 mm of ashfall. Once ash addition started again the unit began to shutdown more regularly; for 2 to 6 minutes every 15 to 30 minutes. After the 3 minutes taken to get back down to the (slightly elevated) temperature the unit could run at while blocked with ash was taken into account, the cold air was running at close to room temperature or even above for 30% to 50% of the time. The temperature of the cold air while the compressor was stopped gradually increased each time the compressor shutdown, until it exceeded room temperature, and the unit began to actively heat the air instead of cooling it. This pattern of shutdowns continued as the system was subjected to more ashfall. The blockages in the back of the unit prevented as much air as usual entering the unit, therefore less ash was being entrained. For the same reason ash within the condenser was not being moved either. While less air entered through the condenser, the fan was still moving at the same speed. Air was still being pushed out the front of the unit, but was also entering from the front, creating a lot of turbulence in and around the front of the fan. Air speeds at the back of the condenser where air usually enters from were measured after 665 minutes, and the addition of ~67 mm of ash, results are illustrated in figure 3.24.

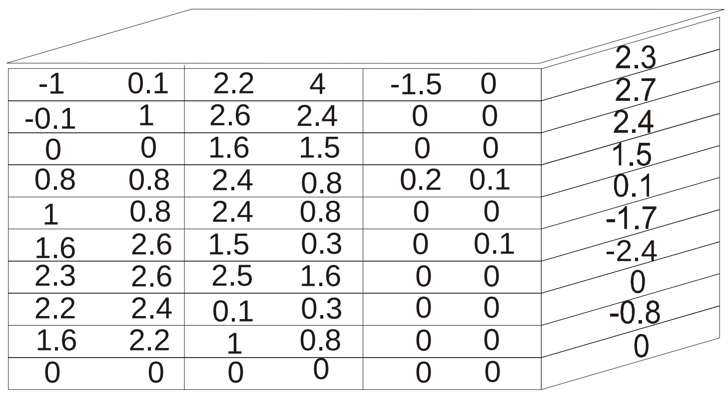

Figure 3.24: Airflow in km/h at the outside of the exterior condenser after 665 minutes of testing (system subject to a total depth of ~67 mm of ash). Negative values indicate air being blown outwards rather than sucked inwards. The unit is effectively blocked at this point.

The pattern of shutdowns for 2 to 6 minutes every 15 to 30 minutes continued until the end of ash addition at 95 mm. Figures 3.25 and 3.26 illustrate blister like accumulations of ash blocking the condenser after 85 mm of ashfall. The unit was run one more time (without the addition of ash) on the following day, having had the chance to cool down overnight. After being left for 4 hours it was monitored for one hour to ascertain whether there had been any change in performance due to being run without ash in the atmosphere. Results are plotted in figure 3.27.

Figure 3.25: Blister-like accumulation of ash on the external grill of the condenser after ~85 mm of ashfall. Note there are also substantial blockages internally, between condenser fins.

Figure 3.26: Accumulation of ash on the condenser after ~85 mm of ashfall.

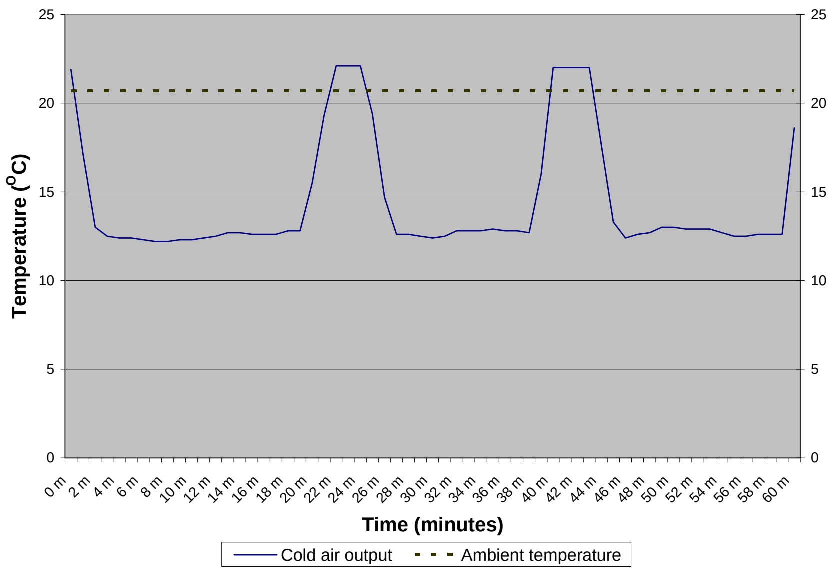

Figure 3.27: Toshiba unit output temperature from 4 hours after the end of ashfall. The peaks indicate external unit shutdowns as internal compressor pressures exceeded limits.

The average output temperature during this time was 14.5^{O}C, including the times during which the compressor had shutdown. This means it was running at 55% of normal performance by the end of testing compared to it's capacity before the addition of volcanic ash, assuming a pre-testing output of 10.2 degrees and an ambient temperature of 20.7 degrees. Although the unit was therefore having some cooling effect, every time the compressor shutdown there existed the risk of the high pressure switch not resetting, and the unit not restarting without manual intervention. The first time the compressor shut down was after 35 mm of ashfall. Allowing for a small margin of error, this indicates the unit could not be relied upon to provide sufficient cooling when subjected to at most ~ 30 mm of ash.

3.5.7 Testing limitations

This testing did not take into account any electrostatic charge held by the grains, which would be present during an ashfall (Gilbert et al. 1991). The electrical charge should not affect the degree to which the particles adhere to air-conditioner surfaces, as the units are grounded, however electrostatic attraction may cause or enhance the creation of accretionary lapilli (Gilbert et al, 1991). As the ash used in this experiment was not electrostatically charged and was only being dropped from a height of one metre, accretionary lapilli could not form, and thus was not a part of the experiment. The lack of large masses of accretionary lapilli is unlikely to alter the results in any significant way; lapilli size particles are unlikely to be sucked into air-conditioning units unless they face skywards. Testing did not include this scenario.

The trials using wet ash have some limitations. In order to be able to freely scatter ash onto the testing apparatus and air-conditioning unit, the ash needed to be dry first – damp or wet ash sticks together. While this can happen to a degree to ash wetted by moisture in the atmosphere (e.g., with the formation of accretionary lapilli), air-fall ash does not stick together in large masses to the same degree that it would in a container or a sieve. Therefore it was necessary to sprinkle dry ash and mix it as it fell with a mist of water from a spraying unit. As a result the ash itself may not have been as wet as it could have been in an actual eruption during rain. However spraying water into the path of the ash ensured that the unit itself was wet, and that at least some of the ash was damp, which in turn would increase the ability of the ash to adhere to the unit.

The effects of wind were also not included in testing. Strong winds may blow more ash into the condenser than the still conditions simulated in the tests. In this case the time and amount of ash needed to cause blockages could be less than results indicate.

3.5.8 Discussion: Air-conditioner performance in ashfall

In both wet and dry scenarios the Mitsubishi electric air-conditioner did not appear to experience anything more than minor temperature fluctuations. This unit was tested with a simulated ashfall of up to 10 mm thickness occurring over about 4.5 hours. No drop-off in performance was observed; output temperatures remained within 0.4^{O}C of initial temperatures achieved by the unit before any ash was added. To a large extent the unit appeared to be self cleaning; ash would quickly pass through the system without being trapped. Trace amounts of ash did adhere to the condenser fins, but the temperature of the cooled air - and thus performance - was not affected.

These results differed substantially from those of the Toshiba unit. There were two reasons for this. Firstly the smaller size and different fan configuration of the Mitsubishi unit resulted in faster airflow through the unit, the maximum airspeed on the outside of the condenser for the Mitsubishi was recorded at14.5 km/h, as opposed to 5.2 km/h on the Toshiba. Averaged out over the entire face of the condenser, the airspeed for the Mitsubishi was 10.6 km/h, the Toshiba was 2.5 km/h. These values differ partly because of different fan size, shape and speed, but also because the Mitsubishi unit pushed air through the unit rather than sucking it through, as the Toshiba did. The air had therefore already travelled through the Mitsubishi condenser, and was exiting it, but was measured as it entered the condenser on the Toshiba unit, prior to reaching the fan. Despite these different setups these values still reflect the airspeed through the condenser, which results indicate is a key factor in determining the amount of ash that lodges within the unit, and ultimately in unit performance. The areas in the Toshiba unit where airspeed was greatest (5.2 km/h) still blocked up readily, whereas the area with the slowest airflow in the Mitsubishi unit, at 5.7 km/h remained unblocked. This does not reflect a critical speed at which blockages occur, but a difference in fan configuration. This is the second important difference between the units. Because the Mitsubishi unit pushed air through the condenser, any blockage caused by ash would continue to be subjected to positive air pressure from the fan, and could therefore be moved subsequently. Blockages in the Toshiba condenser caused the airflow to be diverted to other parts of the unit. Reduced pressure on those blockages meant they were less likely to be dislodged without manual intervention.

For these reasons ash was cleared more effectively from the Mitsubishi than the Toshiba. This difference illustrates that no specific “safe” air speed for the effective removal of volcanic ash from condensers can accurately be assigned generically to air-conditioner units. Unit set-ups differ, not just in fan speed and size, but in placement of the fan relative to the condenser, condenser shape and in condenser fin spacing. Grain size and weather conditions will also have an effect on what air speed will be sufficient to clear blockages. Despite these variables it is evident that faster speeds are better, and the >10 km/h average air speed through the Mitsubishi electric unit was sufficient to prevent ash accumulating in the condenser. The fact that air moving at 5.7 km/h through areas of the Mitsubishi did not deposit ash, but air moving at 5.2 km/h resulted in blockages in the Toshiba indicates that the air speed required to prevent ash lodging in the condenser for this type of unit may be greater than in the through-wall type unit.

In both wet and dry Toshiba tests there was an initial rise in temperature. During the dry test, output temperatures rose by $1^{O}C$ after 135 minutes of testing, or 6.5 mm of ashfall. In the wet test a similar result was seen in that it took 135 minutes for temperatures to rise by one degree, but by this time there had been over 14 mm of ashfall. In both cases there was some ash adhering to the condenser, but not enough to cause blockages or significantly reduce airflow. These results suggest that initial temperature rises are caused not by reduced airflow but by an insulation effect due to ash covering parts of the condenser. This effect appears to be fairly small, in the order of increasing output temperatures by up to about $2^{O}C$. It appears to start occurring after as little as 1-2 mm of ashfall, as rises in temperature began exceeding normal fluctuation levels within minutes of ash addition beginning. Increases in temperature after 10 mm – 15 mm of ash, can be attributed not only to this insulation effect but to a reduction in airflow, caused by the blockages in the condenser. During the dry testing the maximum amount the temperature increased by before the unit began to shut itself down as the compressor overloaded was $3.6^{O}C$, during wet testing it was $2.5^{O}C$.

After the Toshiba unit had been cleaned out following the dry test, it was unable to regain the low output temperatures close to $10^{O}C$ that it was able to pre-testing. This indicates either compressor damage or coolant leakage had taken place in the first (dry) test. Either of these causes would be induced by abnormally high pressure in the compressor, in turn caused by ash blocking airflow through the condenser. Therefore even if air conditioners manage to keep running during heavy ashfall, once the compressor overload starts being tripped, there is a risk of damage to the compressor, ultimately reducing unit efficiency.

Fin spacing appeared to have little effect on blockages. The narrower spacing between fins on the Mitsubishi was expected to cause more blockages, but due to the faster airspeed this did not occur. This is likely only to become an issue if a coarse grainsize ash (larger than the spacing between fins) impacted a horizontally mounted condenser, as is sometimes done on rooftops.

Although there is a drop off in performance for conventional split system units after a few millimetres of ash, the slightly elevated temperatures will in most instances be insufficient to cause damage or shutdowns for end users of air conditioning systems. Once blockages in the condenser reduce the dissipation of heat sufficiently to cause the compressor to overload, performance will in most cases drop below levels required to maintain adequate cooling. This effect is worsened by the fact that the interior unit can continue to function without the exterior unit running, but will blow air at room temperature, or even heat the air while the compressor is shutdown. Blockages sufficient to cause the compressor to overload will depend on unit and compressor type, but this appears to be able to happen from between 30 mm and 50 mm of ashfall. This could be sooner, depending on weather conditions and unit type. The variables present mean that these numbers need to be treated with caution. After the cycle of shutdowns begins, the combination of elevated output temperatures and periods of either no cooling or active warming will constitute air conditioning failure, as performance loss will approach 50% of usual. This figure may drop further if the compressor sustains damage, to zero once the whole unit shuts down, as seen in the Toshiba dry ash test.

While determining the abrasion of bearings was not an objective in these tests, the units were monitored for adverse effects of this type. None were noted on the units themselves during testing, although it is expected that fan bearings could eventually suffer increased wear from abrasion in the long term if not adequately maintained, as ash may adhere to lubricants and remain in contact with moving parts well after ashfall has ceased.

3.5.9 Cleaning ash from condensers

Cleaning dry ash from condensers can be achieved through the use of compressed air. The small gaps between fins on the radiator prevent brushes being useful except for removing ash from the outside. Care must be exercised as the fins are very thin, and prone to bending even when only a little force is applied. Water blasting is too powerful and will result in the radiator fins sustaining damage. If compressed air is not available gentle hosing may get rid of some of the ash, but a thorough job needs to be done as any ash not removed by water will dry and harden, making it almost impossible to subsequently remove as it is very difficult to access. If ash is already wet then gentle hosing is an acceptable method of ash removal from condensers, however if a unit has been running, the heat from the condenser may have dried out some of the ash, so where possible compressed air should be tried first. This could be problematic if ashfall is still taking place, due to possible damage occurring to the air compressor if it is sucking in ash laden air. If no other methods are available, simply banging the top of the unit will help to dislodge loose ash. In dry conditions vacuuming the condenser will also help to remove much of the ash.

Where units are acting as heat pumps, the cold wet evaporator will potentially be harder to clean, since even dry ash will be wetted as it lodges in the evaporator, in the long term this is more likely to harden into a solid deposit that is difficult to remove.

3.5.10 Filter performance

The filter used to prevent large amounts of ash entering the test area was EU3 media, designed to remove 80% of particles at 10 microns, but only 45% of particles at 1 micron. During these tests the filter failed in two ways – as well as letting some ash through (figure 3.8A), the filter quickly became choked with ash, restricting airflow. For the purposes of the experiments being conducted, this necessitated regular cleaning (vacuuming both sides) of the filter.

These types of filters are typically used for fresh air filters in exchanges, usually as a backup for when air conditioners are not providing the amount of cooling required. Under normal circumstances these filters can be cleaned or replaced quickly enough that blockages do not occur. However the amount of ash potentially present in the atmosphere during ashfall far exceeds usual amounts of dust and airborne particulates. The volumes expected during all but very light ashfall will cause filters to quickly become choked with ash and restrict airflow. Furthermore distal volcanic ashfall can potentially be very fine, the grainsize of the smallest particles can be <1 μm, (Heiken & Wohletz, 1985). Fine ash can therefore pass through most air filtering systems. Even self-cleaning filters are not likely to be effective, as these use high pressure air to flush material out from filters. This air would have to come from inside the building during ashfall, as compressors would quickly fail if ash were ingested. This would lower the pressure inside the building, causing ash laden air to be drawn inside. Any type of filtration is therefore unlikely to work effectively during ashfall.

3.6 Mitigation options

Mitigating the impacts of volcanic ash on air conditioners can be undertaken in a variety of ways. Most of these need to be implemented prior to ashfall. The most effective means of mitigating these impacts is to use air conditioners with more powerful fans per unit area of the condenser. Faster airflow through the condenser results in less blockages occurring. Those types of air conditioner (such as through-wall units) that push air through the condenser will also be more effective. In most areas potentially subject to ashfall, volcanic eruptions are still a low probability. Despite their potentially high impact, retrofitting infrastructure with more robust air conditioners is therefore economically unfeasible. However in areas with a high probability of ashfall (and thus higher risk) this option could be considered when new units are installed in essential services.

While most modern air conditioners have automatic reset switches on their compressors to restart units after overloads, this is not always the case. Automatic restart after compressor overload will keep units at least partially operational for more time after heavy ashfall has blocked condensers. This will give technicians or engineers additional time to reach and repair or clean out units as required. Units may still operate for hours or days after initial shutdowns begin to occur. More efficient cooling may also be gained when units are operating under excess load and the compressor is shutting down, by stopping the interior unit running while the exterior unit is shut down. In this way interior air would not actively be warmed by the air conditioner during these times. This will only make a small difference, but could be significant.

Filtration has been shown to be ineffective for the volume of ash experienced during ashfall (section 3.5.10). However a simple way of reducing the amount of ash ingested by air conditioners is by either placing them in sheltered areas – such as under deep eaves, or by emplacing a small (preferably sloping) roof over the unit, so that ash falling sub-vertically cannot directly enter the unit. Deep eaves on the cable television relay building in Trevelin are thought to have given the air conditioning unit some protection from the 60 mm of ash received from Chaiten between the 2nd and 6th of May 2008 (section 3.2). Protective shelters need to be built strong enough that they do not collapse under tephra loading, or have steep enough pitches that ash will slide off. Remobilised ash may still be entrained with ingested air, but the amount will be reduced.

Once ashfall has begun the options mentioned above cannot realistically be implemented. If units are at manned premises or in homes, regular cleaning will help to alleviate blockages as ash accumulates (section 3.5.9 describes cleaning methods). Many air conditioners are deployed in commercial or industrial situations where they are completely unmanned. Some locations (such as rural telephone exchanges) can be quite remote. Getting to air conditioners will be difficult during and immediately after ashfall. Roads may be closed or even impassable, visibility can be severely reduced even where roads are still open, slowing traffic substantially. Chapter 5 discusses driving during and after ashfall. Companies responsible for the maintenance of air conditioners for essential services need to allow for these eventualities in their emergency response planning for volcanic eruptions.

Although it has been shown that air conditioners may operate during ashfall, it is advisable that non- essential units are turned off while ash is entrained in the air. This will prevent unnecessary damage and/or difficult cleanup of condensers.

3.7 Summary

The vulnerability of air conditioners to ashfall has been shown through experimentation to be dependant on airspeed and fan configuration. Faster airspeed through condensers results in less ash lodging within the system, and a more robust unit in ashfall. Common split system air conditioner types were observed to have a slight decrease in performance almost immediately after ashfall began, but it took between 35 mm (wet) and 50 mm (dry) of ash to cause failure. 30 mm is suggested as a maximum amount of ashfall under which typical air conditioner units may safely operate, albeit at reduced efficiency. Exceeding this is likely to cause sufficient blockages in the condenser that compressor damage and shutdowns may follow. It should be noted that in some instances failure may occur before this, as unit configurations vary, and remobilisation of ash or strong winds during ashfall may affect results. This experimentation has nevertheless determined that air conditioner operation remains viable during ashfall, provided monitoring and regular maintenance are carried out. Essential cooling can therefore continue to take place during ashfall, subject to appropriate operating procedures taking place.

CHAPTER 4 THE IMPACTS OF VOLCANIC ASH ON AIRPORTS AND GROUNDED AIRCRAFT

4.1 Introduction

4.1.1 Airborne ash encounters

The problems associated with airborne aircraft encountering volcanic ash in the atmosphere are well appreciated within the aviation industry. From 1973 through 2000, about 100 incidents of aircraft flying into airborne volcanic ash were documented. An average of two reported encounters per year since 1991 have occurred (a large number occurred in that year due to the Pinatubo eruption), further unreported encounters are likely. (Guffanti & Miller, 2002). More have taken place since this time, including 2 aircraft encounters with volcanic ash recorded over Micronesia in November 2002 and a further one in March 2003. One of the 2002 incidents resulted in damage to an Airbus A340, including damaged pitot tubes and light abrasion around engine intakes (Tupper et al., 2004). That occasion involved ash from Ecuador's Reventador volcano, 14,000 km distant; (Tupper et al., 2006). The fact that volcanic ash clouds can still damage aircraft after travelling such distances illustrates why they are a major problem for aviation.

Globally, volcanic ash intersects aviation paths at altitudes over 30,000 ft on approximately 20 days per year (Miller and Casadevall, 2000). Aircraft encounters with volcanic ash clouds usually result in damage to the aircraft; the abrasive nature of the ash causes significant damage to all forward-facing surfaces (including the windscreen). Any protruding parts, for example antennas, probes, ice detectors, angle of attack vanes and pitot tubes are also vulnerable, and may be damaged or even rendered inoperable (ICAO 2001). Jet engines are particularly susceptible to damage from volcanic ash, due to the fact that engine operating temperatures (~1400^{O} C) exceed the melting point of all volcanic ash types. "The ash melts in the hot section of the engine and fuses on the high pressure nozzle guide vanes and turbine blades… causing the static burner pressure and compressor discharge pressure to increase rapidly which, in turn, causes engine surge. This effect alone can cause immediate thrust loss and possible engine flame-out" (ICAO, 2001). Seven cases of engine failure due to ingestion of volcanic ash had been reported by 2002. On three occasions this almost caused commercial passenger aircraft to crash (Guffanti & Miller, 2002).

4.1.2 Previous instances of ashfall impacting airports

Less dramatic, and less common than airborne encounters with volcanic ash are instances of ashfall impacting airports and grounded aircraft. The frequency of ashfall actually landing on airports is far less than airborne encounters, however disruptions to airports due to volcanic activity are more common. These include the closure of airports and/or airspace due to the presence of airborne ash, even if the airport itself is not physically impacted. A database of all known airports that have been affected by volcanic ash between 1944 and 2006 was published as a USGS open file report by Guffanti (2007). This records volcanic activity affecting 101 airports on 171 occasions over 28 countries, and involves eruptions at 46 volcanoes (figure 4.1) (Guffanti et al., 2007). The database includes closures to airports due to ash in nearby airspace, and occasionally volcanic hazards other than ashfall (pyroclastic flows, lava flow, gas emissions and phreatic explosions).

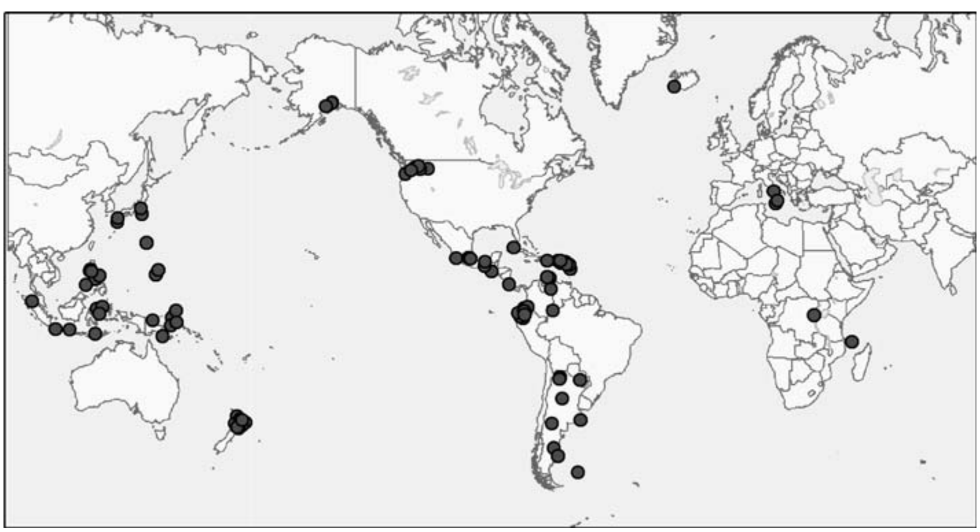

Figure 4.1 locations of airports impacted by volcanic activity, 1944–2006 (Guffanti et al., 2008)

An analysis of the database indicates that between 1944 and 2006 ashfall landed on an airport on at least 73 occasions, with thickness ranging from trace amounts to a maximum of 50 cm (Guffanti et al., 2007). Since 2006 there have been further incidents of this nature. For example the 2008 eruptions of Chaiten Volcano in Chile resulted in disruptions to 5 airports in Chile, 9 in Argentina and 2 in Uruguay (Guffanti, M., pers. comm. 2009). Five of these airports are located over 100 km from Chaiten; one is over 2000 km away. These disruptions ranged from airport closures to cancelled flights.

The risk to life is not so immediate or severe on the ground as it is when flying into an ash cloud. However the potential physical impacts of ash on grounded aircraft and airport infrastructure are considerable. Potential economic effects of ashfall on airports are even more substantial. This is because only a small amount of ash landing on airports, or even being present in proximate airspace may close them down, without any aircraft or infrastructure sustaining actual physical damage.

Minor ash falls on airports will render them inoperative, with damage to both aircraft and facilities (Labadie 1994). Tyler and Reynertson (1981) give details of the clean-up operation at Fairchild Air Force Base, USA after ash falls from Mount St Helens in 1980. Water was used to wet the ash; graders and snowploughs then worked the ash for loaders to pick it up. It was then hauled to a central location where it was buried in landfills. It was noted that around buildings the wind blowing ash from roof tops constantly contaminated previously cleaned areas (Johnston, 1997b). During the 2002 eruption of Mt Etna, Catania's Fontanarossa airport was closed for much of the duration of the 3 month eruption. This was due both to the presence of the ash plume, and to ash falling on the runways. Ash was cleaned up using sweeper trucks, as well as manual labour (Barnard, 2004). During the same period, (November 2002) Ecuador's Reventador volcano erupted, and 4 mm of ash was deposited on Quito's Mariscal Sucre airport. This closed the airport for over a week, while ash was cleaned from airport buildings, runways and aircraft. Clean-up here was entirely by 500 workers with brooms and shovels. Sweeper trucks were unavailable for use in the cleanup (Leonard et al., 2005).

The 1991 Hudson eruption in Chile resulted in cancellations or severe delays for 10 to 20% of all flights on the Atlantic coast passing through the area between Argentina's Trelew and Rio Gallegos (~ 1000 km) from August to October 1991 (Bitschene, 1995). Some airports, for example Camet airport in Argentina were closed due to ash covering runways (BGVN, 1991). Fine ash on the tarmac led to mechanical problems occurring in brake and propulsion systems. At least one engine from an Argentine airlines aircraft was replaced due to ash ingestion (Bitschene, 1995).

In New Zealand, ash impacted airports during the 1995 and 1996 eruptions of Ruapehu (Johnston, 1997a). During these eruptions the Wellington Volcanic Ash Advisory Centre (VAAC) issued over 200 volcanic ash advisories. These resulted in the closure of air-space during eruptive episodes, due to either ash clouds and/or a sulphur dioxide haze. Consequently many flights were either cancelled or re-routed. At least 13 airports were affected, causing flow-on effects well beyond these areas (figure 4.1).

Airport	**1995**	**1996**
Auckland		*A
Hamilton	*	*A
Tauranga	*	*A
Whakatane	*	*A
Gisborne	*A	*
Rotorua	*	*A
Napier	*A	*A
Taupo	*	*A
Wanganui	*	*
New Plymouth		*
Palmerston North	*	*
Wellington		*
Nelson		*

Table 4.1: Closed or disrupted airports during the 1995-1996 eruption (airports that received ash falls marked by A) (from Johnston, 1997a)

The 1996 eruption had the more widespread effect. Seven of these 13 airports received at least trace amounts of ash, with Rotorua Airport receiving the most (~1 mm thickness). This required a substantial clean-up operation. At least two minor aircraft ash encounters were reported, a Saab Metroliner en route to Nelson from Wellington (20 June 1996) and an Aztec en route to Takaka from Wellington (21 June 1996); no serious damage was reported (Johnston, 1997a).

4.1.3 Ashfall hazards to airports and grounded aircraft

Volcanic ash consists of very small fragments (< 2 mm diameter) of volcanic rock and glass. Because of this small size it can easily penetrate small crevices on machinery, vehicles, grounded aircraft, inadequately sealed buildings and even some types of filters protecting machinery or vehicles. The hard nature of volcanic ash renders it extremely abrasive. Therefore any moving parts on machinery are vulnerable – even if they appear to be covered up and protected. For the aviation industry, this penetrative nature can cause significant damage. Removal of ash from aircraft exteriors needs to be performed with care, as the cleaning processes used may cause further abrasion on aircraft surfaces. Airport infrastructure and machinery are also at risk. Different methodologies of cleaning up ash from both aircraft and airports have been employed in previous eruptions (section 4.1.2).

Abrasion is unfortunately not the only hazard posed by tephra to the aviation industry. Aerosols attached to freshly erupted grains of ash are potentially extremely acidic and may cause corrosion on contact with vulnerable surfaces. This is more problematic when rain or mist leaches the acids out of the deposited layer of ash causing corrosion of metal surfaces. Aerosols that escape from the grains of ash whilst still in the air may cause acid rain, which will again cause corrosion. The amount of corrosion that occurs will depend not only on the pH of the leachates, but also on weather conditions. Light rain or drizzle is sufficient to wet ash but not to wash ash off surfaces. Heavy rain on the other hand may be sufficient to help clean ash off aircraft and other surfaces. This in turn causes other impacts to airport infrastructure, such as blocking of drains or downpipes, subsequently causing roofs to leak and surface flooding on the ground.

Less common is damage caused by the residual heat carried in ash from the volcano. Ash quickly cools as it travels through the atmosphere, so this is only a problem for events proximal to airports. This has occurred in the past, when an estimated 88 US B-25 bombers from the 340th Bombardment Group stationed in Pompeii during World War II were covered in ash from an eruption of Mt Vesuvius. The heat from the ash burnt fabric control surfaces, melted or cracked Plexiglas windows and severely damaged all aircraft impacted (figure 4.2). This was in addition to damage from volcanic bombs and lapilli (Kaiser, 2007).

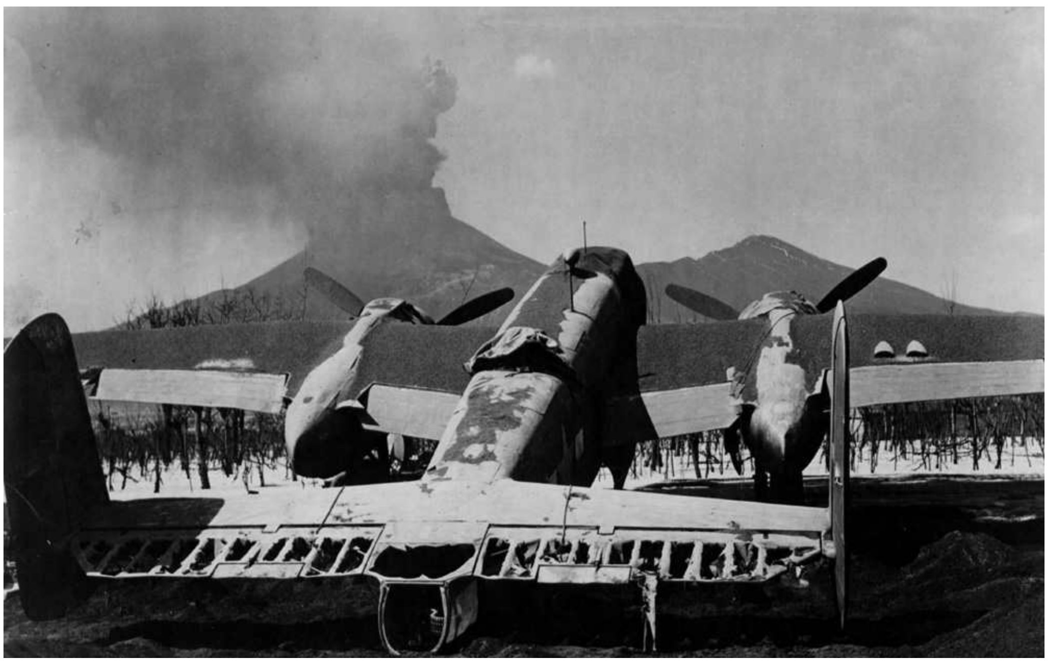

Figure 4.2: Damaged B-25 at Pompeii after ashfall from the March 23 1944 eruption of Vesuvius. Note the holes in the fabric surface of the tail. Source U.S. National Archives and Records Administration

The weight of volcanic ash causes problems, especially when wet. Ash may absorb a large amount of water - up to 50% of it own volume, thus increasing its weight significantly. Large span structures (such as aircraft hangars) run the risk of collapse under such loads. An example of this occurred during the 1991 Pinatubo eruption where over 15 cm of wet ash combined with ground shaking from volcanogenic earthquakes caused numerous hangars to collapse at Clark Air Force Base, Basa Air Base and Cubi Point Naval Air Station (Casadevall, 1992, 1996).

As well as the problems caused by abrasion, corrosion and loading, the slipperiness of small grains of volcanic ash constitutes a hazard in itself. This in part prevents the landing of aircraft on ash covered runways, combined with the risk of the ingestion of volcanic ash by jet engines. The covering of markings on roads, runways and taxiways is also an issue. Ash suspended in the air not only prevents aircraft flying, but causes visibility problems on the ground, exacerbated by people or machinery moving over ash covered surfaces, remobilising it into suspension.

Boeing recommends that aircraft are not operated on runways contaminated with any volcanic ash at all (Boeing, 2004). This assessment is seen by some pilots and airport officials as being overly cautious, given that aircraft can safely operate in dusty desert environments (Giancarlo Guarrera, pers. comm., 2005). Furthermore the International Civil Aviation Organization (ICAO) recognise the possibility of landing and taking off on runways with small amounts of ash – provided several safety issues are closely adhered to (ICAO, 2001). Many pilots however refuse to land on runways with any amount of ash present, thus even minor amounts may close airports until after a clean up has been effected. An example of this was at Fontanarossa Airport during the 2002 eruption of Etna, when on several occasions pilots refused to land, despite airport authorities declaring the airport open and no plume being present (Giancarlo Guarrera, pers. comm., 2005). The risk of any ash being present was sufficient to make the pilots concerned decide to deviate to other ports. For airports to remain open all ash must therefore be removed from airside areas, a time-consuming process which is expensive both in terms of actual physical removal costs and airport closure time.

Thicker deposits of ash are naturally more problematic than thin layers, as physical damage begins to take place, both to airport infrastructure and grounded aircraft. The well-known picture by R L Reiger of a DC-10 that has been rocked back onto its tail at Cubi Point Naval Air Station after 15-20 cm of ashfall from the 1991 Pinatubo eruption, illustrates a more severe impact at airports (Casadevall, 1992). Several of the B-25s damaged at Pompeii in 1944 from the March 23rd eruption were rocked back onto their tails in a similar fashion (figure 4.3)

These North American B-25s were bogged down in dunes of lava cinders, from the eruption of Mt. Vesuivius on 23 March 1944. The weight of cinders and ashes on the tail of the planes was so heavy that the nose was lifted off the ground.

Figure 4.3: Source U.S. National Archives and Records Administration

A detailed account of discussions and recommendations from a 1993 workshop on the impacts of volcanic ash on airport facilities is given in Casadevall (1993). This work gives examples of impacts of volcanic ash on airports from several eruptions in the late 1980’s and early 1990’s. ICAO (2001) has provided guidelines on possible impacts of ash and methodologies for cleaning it up. This chapter seeks to further identify and quantify the impacts of volcanic ash on grounded aircraft, and determine whether existing cleaning methodologies for airports and aircraft are best practice. This is in part based on the more recent experiences of two airports that have frequently been impacted by volcanic ash; Fontanarossa Airport, Catania, Italy (during the 2002 eruptions of Mt Etna) and Mariscal Sucre Airport, Quito, Ecuador (during the 1999 eruption of Guagua Pichincha, and the 2002 eruption of El Reventador Volcano). Further impacts are addressed through laboratory experimentation simulating the effects of ash on aircraft surfaces.

4.2 The 2002 Etna eruption: Impacts of ashfall on Fontanarossa Airport, and Sigonella Naval Air Station, Catania, Italy

4.2.1 Airport background

Fontanarossa is Sicily's busiest airport, Italy's 2nd busiest regional airport and 4th busiest national airport. Over 5 million passengers transited this airport in 2004. The main runway is 2560 m long and 45 m wide, with a 7.5 metre apron each side (SAC, 2007). It is located 30 km from the summit area of Etna. The airport is operated by the *Società Aeroporto Catania* (SAC) which in turn is answerable to ENAC, the *Ente Nazionale per l'Aviazione Civile* or Italian national civil aviation authority.

Sigonella is a joint Italian air force and US Naval Air Station (NAS), located south of Fontanarossa, 38 km from the summit area of Etna. It is a major Mediterranean base for the USA, who operate several different types of aircraft from here. In addition NATO aircraft often transit through this base. The Italian air force operates mainly turbo –prop anti-submarine aircraft from Sigonella.

4.2.2 Eruptive events affecting Fontanarossa and Sigonella

On 27 October 2002, a flank eruption began on Mount Etna that lasted 3 months, finally ending on 28 January 2003. Eruptive fissures opened on the south and east flanks of the volcano, with both effusive and explosive activity ensuing. Aa lava flows caused damage to property proximal to the volcano, while Strombolian and especially Hawaiian style activity created large amounts of basaltic ash that caused damage or disruption to more distal areas, including Fontanarossa airport, and to a lesser extent NAS Sigonella. This eruption resulted in more ash falling on Catania than there had been in living memory. During the first three days of the eruption accumulated ashfall in Catania measured approximately 1.6 mm (Barnard, 2004). Fontanarossa, located on the southern edge of the city, received a similar amount of ash.

During November and early December 2002 fieldwork was undertaken in Catania to ascertain the effects of the volcanic activity, especially basaltic ash, on the populace and infrastructure of the province of Catania. Further fieldwork and interviews with the operations manager of SAC (Giancarlo Guarrera) were conducted in mid 2005. Major Colombo of the Italian air force was interviewed at NAS Sigonella to ascertain impacts of ashfall on that airport.

4.2.3 Impacts on radar systems

Radar systems are not present at Fontanarossa airport; the Italian military controls all airspace in Italy, and all local radar equipment is situated at NAS Sigonella. While located only a few kilometres away from Fontanarossa, the ash plume missed the base on most occasions during the 2002 eruptions, radar equipment was only directly impacted by volcanic ash on one occasion. This involved only trace amounts of ash, which had no noticeable physical effect on any radar equipment (Major Colombo, pers. comm., 2005). The radar equipment present could not detect the ash plume, therefore detection relied on visual observation. For this reason it was ruled by ENAC that flights could only operate during daylight hours.

4.2.4 Impacts on runways

Ashfall landed on Fontanarossa on many occasions during the course of the 3 month long eruption. This happened so frequently that airport authorities kept no records of the number of times it occurred or the amount of time the airport was closed. In each case ashfall on runways and taxiways was cleaned up at the earliest opportunity, as the airport operators (SAC) were striving to keep the airport open as much as possible. Sweeping usually commenced as soon as ashfall began. Although this could mean the same areas needed to be cleaned more than once, the cost of running sweepers for longer was far outweighed by the cost of the airport being closed. Because of this rapid approach to cleaning the amount of accumulated ash never exceeded more than approximately 1 mm. This was still enough to obscure runway markings, create a slippery surface and the possibility of engine damage due to the ingestion of ash. Residual ash was sometimes left on the runways after cleaning. This caused problems as it was remobilised by aircraft as they landed and took off, creating problems for following aircraft (Guarrera, G., pers. comm., 2005).

4.2.5 Runway clean up operations and procedures

Runway and apron clean-up was preformed by vacuum/sweeper trucks, some of which were street sweepers leased from the local council (ANAS). The trucks would sweep up and down the runway longitudinally. The entire 150,000 m^2 runway area would take 30 hours for a single truck to clean approximately 1 mm of ash from the surface, though this was usually sped up by 2-4 trucks working at once. Not all areas always required cleaning; sweeping would usually take between 2 and 8 hours depending on the amount of ash present on the runway. Water tankers were used to remove residual ash, washing ash to the grassed areas on the sides of the runway. These operated by driving across the runway rather than along it, and used high pressure water. The green areas (safety strips) were wetted, then "ploughed" with a pulvimixer to entrain ash in to the soil, followed by rolling the earth to assist in preventing remobilisation of ash. Using a pulvimixer and roller, 1000m^2 took about one hour to cover. Joints between slabs on the runway and taxiways were also cleaned, using a small vacuum (SAC, 2003). Since the 2002 eruption the airport has purchased an additional street sweeper and water tanker to help in future ashfall cleanups (Guarrera, G., pers. comm., 2005).

Figure 4.4: Clean up at Fontanarossa airport

4.2.6 Impacts on buildings and services

As each ashfall was only ~ 1 mm there was time to sweep clean roofs, canopies balconies etc before any build up of ash occurred. Drains and downpipes were cleaned using high pressure water. No adverse impact occurred due to the rapid cleanup (Guarrera, G., pers. comm., 2005).

4.2.7 Impacts on grounded aircraft

Aircraft were very rarely parked at Fontanarossa during the eruption. Those few that were left outside for any length of time had engine intakes covered with tarpaulins. These were the only parts of aircraft that were covered. Before flying a visual inspection was conducted prior to starting engines. Once engines had been started up they were checked for a sulphur smell which was thought may have indicated the presence of ash (Guarrera, G., pers. comm., 2005). Fortunately ashfall did not impact the airport on the few occasions aircraft were left outside, therefore ash did not physically land on grounded aircraft at Fontanarossa during this eruption.

As a precautionary measure most of the military aircraft stationed at NAS Sigonella were moved to Sardinia for the duration of the eruption. Therefore on the one occasion when light ashfall landed on the base there was no impact on grounded aircraft (Major Colombo, pers. comm., 2005).

4.2.8 Operational impacts

Decisions to officially close Fontanarossa were made by a crisis team (NVO) who considered the opinions of both pilots and INGV (the *Istituto Nazionale di Geofisica e Vulcanologia*), as well as any SIGMETs or NOTAMs (ENAC, 2003). This team reported to the director of the airport, who in most cases had the final say on closing Fontanarossa. The decision to close was automatic if ash was present on the runway, but the wind direction also had a strong influence. This not only dictated the location of the plume but in which direction takeoff and landing would be in. On cloudy days it was not always apparent where the plume was. The same applied at night, consequently, during the eruption the airport adopted a timetable of opening from 7 am until 6 pm where possible (*La Sicilia,* 28/12/02).

While the airport director usually decided who closed the airport officially, pilots could decide whether or not to land in Catania – even if the airport was officially open. Decisions were often made in-flight, as pilots could divert after making a visual assessment of the conditions around Fontanarossa. This would often then result in that airline diverting all subsequent flights that day to Palermo or Reggio Calabria. Another reason given for diversion was that pilots would not always believe that the runway had been adequately cleaned of ash. Some pilots refused to fly into Catania at all for the entire duration of the eruption. The strength of the pilots association in Italy meant that if a pilot declared conditions to be dangerous then the pilots association would declare the airport closed, much to the frustration of airport officials (Giancarlo Guarrera, pers. comm., 2005).

No additional staff were required during the eruption, despite additional sweeping and cleaning needs.

4.2.9 Economic impacts

Ongoing closures meant that the economic damage caused to the airport by the eruption was significant. Not only did ash covering runways cause closures, but airspace was also closed by the plume. The fact that some pilots refused to fly into Catania during the eruption, preferring to land in Palermo, even when Fontanarossa was open, cost the airport even more money. While SAC declined providing an estimate of costs, it was said by the mayor of Catania (Umberto Scapagnini) to be around €500,000 per day (*La Sicilia*, 29/10/02).

4.2.10 Lessons learned from the 2002 Etna eruption

Subsequent to the 2002 eruption, the airport operators SAC undertook the writing of a manual detailing procedures for operations around and removal of volcanic ash: "*Cenere Vulcanica: procedure per la gestione, i controlli ed il monitoraggio della sicurezza ed agibilita' delle aree di movimento aeroportuali*" (SAC 2003). This translates as "Volcanic Ash: Procedures for it's management and control, and the monitoring of the safety and operation of the airport's area of maneuvering" (this equates to the airside part of the airport). This is an unpublished manual designed for use by Fontanarossa airport, based largely on experience gained during Etna's 2002 eruption. It describes recommended courses of action for Fontanarossa to take before, during and after an eruption. Most importantly it gives timeframes for cleaning methodologies. These timeframes are extremely useful for pre-eruption planning at any airport. A synopsis of its recommendations in the event of an eruption are:

Pre-event: (eruption pending, airport open)

- Cover exposed equipment (especially computer or electronic equipment) with plastic sheeting
- Put any other equipment not in frequent use inside buildings
- Arrange additional means of cleaning paved areas, e.g. hire street sweeper trucks and water tankers.
- Arrange for the supply of additional (extraordinary) quantities of water
- Locate areas suitable for temporarily storing volcanic ash once it has been removed from the airport.
- Acquire additional auxiliary electrical generators.
- Acquire lime to help with the stabilisation of ash
- Supply water hoses to the temporary ash storage area

During the event (airport closed to flights)

- Cover any electronic equipment exposed to the elements.
- Move any other equipment still outdoors inside.
- Begin cleaning runways and taxiways
- Clean other areas airside
- Wet the safety strips (green areas beside runway) and plough in ash with pulvimixer, followed by a roller.
- Thoroughly wet the ash storage area, keep water spraying over the ash.

After the eruption has ceased

- Uncover equipment that has been covered up
- Plough lime into green areas to help stabilise ash.
- Continue to wet safety strips beside runways
- Remove ash from temporary storage area(s)
- Clean elevated surfaces (balconies, roofs, canopies etc).
- Inspect runways/taxiways/aprons
- Resume normal airside operations
- Clean other areas (e.g. carparks).

Procedures for removing volcanic ash are also mentioned, as described in section 4.2.5. These procedures list the time taken for different numbers of machines to clean different areas. The results of these give the following timeframes for cleaning (table 4.2).

Activity	Equipment used	Area covered per machine per hour
Sweeping and vacuuming (or blowing as required) volcanic ash, moving along the length of the runway	Large vacuum sweeper	$5000m^2$
Washing the runway surface, with high pressure water, driving across the runway widthways	Water tankers	$7500m^2$
Ploughing ash into green areas and subsequently rolling it	Roller-compactor/ pulvimixer	$1000m^2$

Table 4.2 Runway cleaning timeframes

The 2002 eruption of Etna provides a good example of the considerable economic damage that ashfall and ash plumes can cause, even when no actual physical damage is sustained. The frequency of explosive eruptions at Etna has given the airport operators (SAC) significant experience in dealing with light ashfall, adding weight to their recommended procedures and methodologies.

4.3 The 1999 Guagua Pichincha and 2002 Reventador Eruptions: Impacts of ashfall on Mariscal Sucre Airport, Quito, Ecuador

4.3.1 Background

Much of this account of the impacts of the eruptions of Guagua Pichincha and Reventador on Quito's airport is included within Leonard et al., 2005, available within as appendix 5. The aviation section of that article was written by this author. Section 4.3 of this chapter includes and adds to that information.

4.3.2 Airport background

Quito's international airport (Aeropuerto Internacional Mariscal Sucre) is Ecuador's main airport. Approximately 25 international and 50 domestic flights operate daily through this airport, together with cargo, military and private flights. The airport runway is approximately 3100 metres long by 46 metres wide, with taxiways of a similar length. Mariscal Sucre is located only 14 km from the summit of Guagua Pichincha volcano, and 93 km from Reventador volcano.

4.3.3 Eruptive events affecting Mariscal Sucre

The airport was subjected to ashfall from eruptions from both Guagua Pichincha (during October to December 1999 activity) and El Reventador Volcano (in November 2002). On three occasions during those eruptions the airport was forced to close for a week to 10 days in order to clean ash from the runways, airport infrastructure and from aircraft grounded on site during the eruptions.

During the Guagua Pichincha eruption in 1999, 2 - 3 mm of ash was twice deposited on Quito airport; the 2002 Reventador eruption resulted in a 4 mm covering of ash. In all cases grounded aircraft were covered by ash. While there was no physical damage to aircraft and airport infrastructure during these eruptions, economic damage was significant, due to airport closure time, aircraft being rendered inoperable while the clean-up took place and the costs of the clean-up itself.

4.3.4 Impacts on Runways: Clean up operations and procedures

Cleaning the 285,000 m^2 of runways and taxiways/aprons was the most time-consuming task related to the ashfall. In each eruptive case the runway cleanup was performed by 500 labourers with brooms, in the absence of available machinery (figure 4.5). One sweeper truck was owned by the airport, however this was found to be ineffective in removing ash.

Figure 4.5: Manual runway cleanup at Mariscal Sucre Airport after the 2002 Reventador eruption. Photo courtesy of Mariscal Sucre Airport.

Ash on the green areas around the runway was wet with a water tanker to prevent it from being remobilised onto the swept areas. A coagulation chemical supplied by Continental Airlines and sprayed with trucks was also used to stabilise ash in these green areas. The on-tarmac ash being swept was only slightly dampened (with tankers every 30 minutes), as wet ash was found to become sticky and more difficult to clean up. The time taken to clean the runway and taxiway of the 2-4 mm of ash was at least 7 days for each eruption, using 500 labourers working 15 hours per day. This equates to 52500 hours spent sweeping and bagging ash. On average each worker could thus clean around 5.4 m^2 per hour, including the time taken to bag ash, load it onto a truck, and breaks.

4.3.5 Impacts on buildings and services

Cleaning up the airport buildings and other infrastructure was performed manually, with brooms and shovels. The 4 mm maximum of ash that fell on the airport during both the 1999 Guagua Pichincha and 2002 Reventador eruptions was not sufficient to cause structural damage to buildings. Air-conditioning units were not installed at the airport at this time. The lack of vulnerable infrastructure resulted in the airport proving to be robust enough to survive the ashfall undamaged. While ash blocked stormwater systems in some parts of the city in 2002, this problem was not significant at the airport as insufficient rain fell in this area in the hours and days after the eruption to cause this to happen.

4.3.6 Impacts on grounded aircraft

In 2002, the airport was given 5 hours warning of an eruption from IGEPN (the *Instituto Geofisico, Escuela Politecnica Nacional*), but no mitigation was initiated at that time. The airport was closed one hour before ash began to fall. Rapid responses were required to protect vulnerable parts of the aircraft parked on the taxiways and aprons of the airport. At the onset of ashfall, aircraft nose-cones and windshields were covered by tarpaulins. Landing gear, engines and pitot tubes were also covered. Wings were not covered, but all flaps/spoilers etc were fully closed or retracted.

Ash adhered to the aircraft, but was dry enough to be removed by a person blowing on it. The ash remained on the aircraft from 12 to 48 hours, depending on when crews cleaned each aeroplane. Aircraft were moved with tow vehicles rather than starting jet engines or auxiliary power units in the presence of ash. Cleaning was performed using water from an airport fire truck. This only took 10 to 15 minutes for a medium sized passenger aircraft (e.g. a Boeing 737). After cleaning, full service checks were preformed on each of the aircraft to ascertain whether any damage had been sustained. No abrasion was seen to have occurred when the ash was washed off with the fire hoses. Similarly no ingress of ash to the interior of wings etc was observed. In some cases cleaning was performed manually, using brooms.

No corrosion was noted, though this was unlikely as the ash remained dry. The tarpaulins (secured with adhesive tape) were successful in protecting the vulnerable parts of the aircraft. An Airbus representative from Miami flew in to oversee the cleaning and assess any ash damage. Authorities stated that they did not need to open up the engines for inspection, but full 'service inspections' were conducted.

Figure 4.6: Aerogal Boeing 727covered in ash from the Reventador 2002 eruption. Note the covered windscreen and nosecone, front wheel assembly and engine intakes. Photo courtesy of Mariscal Sucre Airport.

4.3.7 Operational impacts

The decision to close the airport was the responsibility with Ecuador's Dirección General de Aviación Civil (DAC). This body is in communication with Ecuador's Geophysical institute (IGEPN) and the Ecuadorian meteorological service. IGEPN also communicates directly with the Washington VAAC, which communicates internationally. IGEPN staff noted that the decision-making process was not well established, with some convincing required to close the airport (Leonard et al., 2005). This was in part due to pressure from local carriers, who had more to lose than larger international airlines when Mariscal Sucre closed.

4.3.8 Economic impacts

These interruptions to normal service proved costly for both the airport and for carriers, especially local airlines. The cleanup itself was comparatively cheap (in Ecuador labourers could be cheaply hired for \$0.75 – \$1.00 US per hour) therefore the entire clean up would cost ~\$50,000). This solution may not have been as economically feasible in nations with higher pay rates. However the length of time that the airport was closed for caused a significant loss of income.

The national airline in Ecuador (TAME) was particularly affected by the 2002 Reventador eruption. Seven aircraft were trapped on the ground for the duration of the eruption and clean-up. These seven aircraft represented a large proportion of the airline's total fleet of 11. While advanced warning times may have given the airline more time to move the aircraft, availability of pilots to fly the planes would still have been a problem.

4.3.9 Lessons learned from the 1999 Guagua Pichincha and 2002 Reventador eruptions

Despite the low-tech approach to cleaning the runways, these eruptions have demonstrated that it is possible to remove vast amounts of volcanic ash with little more than brooms, provided a cheap labour force is available. More importantly the cleaning methodologies employed to remove ash from aircraft have proved to be effective. These give an option for airport operators and airlines to consider in future ashfalls.

In terms of risk management, the delay in closing the airport after advice had been given of an impending eruption proved to be costly. This delay illustrates the importance of having a well established decision making system, and of good communications with volcano monitoring agencies. The 2002 Reventador eruption demonstrated the impact that closing an airport can have on local carriers; prolonged closures can severely threaten their business. As a result they have a greater interest in keeping airports open, to a higher risk threshold than large international airlines.

4.4 Aircraft surfaces: Susceptibility to corrosion and abrasion.

The experiences of Mariscal Sucre and Fontanarossa airports were both valuable in terms of determining impacts on the operation of airports during and after ashfall, but the potential for damage to grounded aircraft was fortunately not realised in either case. Corrosion and abrasion to aircraft surfaces remains a real threat if grounded aircraft are subject to ashfall.

4.4.1 Ash properties causing corrosion

Ash collected from volcanic plumes commonly has a coating to particles, which is interpreted to be sulphuric acid (Cadle et al., 1979; Casadevall et al., 1984; Rose et al., 1980). Soluble components (salts) are also present, increasing the conductivity and corrosiveness of ash (Rose, 1977). This is borne out by instances of acid rain in the vicinity of volcanoes, which has been found to have a pH as low as 2 (unpolluted rainwater has a pH of 5.8) (Gíslason et al., 1996), or at Sakurajima volcano a pH <1 (ICAO, 2001). Matsumoto et al. (1988) conducted tests on various metals left outside for a month in sporadic ashfall from Sakurajima volcano. Deterioration was found to occur strongly in aluminium, followed by steel, galvanized steel, copper and then stainless steel. Numerous historic instances of ash and ash leachates causing corrosion on contact with metals have been recorded (e.g. Bitschene, 1995; Blong, 1984; Blong & McKee 1995; Johnston, 1997). The corrosive properties of ash are well established, but to date there have been no significant instances of corrosion from ash on aircraft, possibly in part due to the rarity of ash impacting grounded aircraft, and the speed with which it is usually cleaned up.

4.4.2 Aircraft surfaces

Aluminium alloys are used in aircraft manufacture, as pure aluminium does not have sufficient strength for structural use. While much stronger than pure aluminium, alloys are known to be more susceptible to corrosion (Banis et al., 1999). Corrosion is a common occurrence on aircraft especially around fasteners where holes drilled through cladding and alloys allow the penetration of water (D. Good, Air New

Zealand, pers. comm., 2009). These areas are also susceptible to galvanic corrosion, depending on the type of fastener used, and fretting corrosion if any movement is present. Any corrosion degrades the mechanical performance of the alloy and can cause metal fatigue, which eventually may threaten the integrity of the aircraft (Petroyiannis et al., 2005). For this reason any unpainted alloy skins are usually clad in pure aluminium to provide corrosion resistance. Cladding normally makes up about 5% of the total skin thickness (D. Good, pers. comm., 2009). Skin thicknesses may vary slightly depending on use, but are commonly ~1 mm thick. Pure aluminium is used as not only is it less susceptible to corrosion than aircraft alloys, it is anodic to the core alloy. When exposed to a corrosive solution, current flows from the anodic cladding through the metal to the cathodic core. This dissolves the cladding preferentially, protecting the core (and thus the strength of the skin) electrochemically (Petroyiannis et al., 2005). The unpainted areas of aircraft vary between airlines, but frequently include the leading edge on wings and tails. Some airlines (e.g. American Airlines) leave most of the aircraft unpainted.

While providing some protection, thin aluminium cladding can be compromised; it is easily scratched, and these scratches may penetrate through to the alloy beneath. This could be problematic for cleaning volcanic ash off aircraft. Testing has shown that some electrochemical protection of 2024-T3 alloy is given by the surrounding aluminium, even when the alloy is exposed in scratches (Petroyiannis et al., 2005), but it is unclear how much corrosion could still occur on these surfaces if impacted by volcanic ash and ash leachates. The extent to which abrasion can occur on aluminium surfaces when ash is being cleaned off is also unclear.

4.4.3 Laboratory work

Experimental work was conducted on aircraft skins, to determine timeframes over which acidic leachate damage could occur from ash, and the potential for abrasion from different cleaning methods when removing ash. Two of the most commonly used alloy types were sourced from Air New Zealand; 2024-T3 (a copper-magnesium aluminium alloy) and 7075-T6 (a copper-magnesium-zinc aluminium alloy). Table 4.3 lists alloys used as external skins on commercial aircraft, and illustrates the common use of 2024-T3 and 7075-T6 on aircraft skins (in bold type). New aircraft models such as the Airbus A380 and Boeing 777 use more advanced alloys (including titanium alloys) that were not available at the time of testing.

Aircraft type Area used	Airbus A319, A320, A321	Airbus A380	Boeing 707, 727, 737, 747	Boeing 737-300, 757, 767	Boeing 777
Fuselage/body skin/flaps	**2024-T3**/7475	A6013 HDT	**2024-T3**	**2024-T3**	7150 T77/2XXX-T3
Wing – top skin	7150	A7055	**7075-T6**/7178	7150-T651	7150 T77
Wing – bottom skin	**2024-T3**	A2024 HDT	**2024-T3**	2324-T39	Ti 15 – 3, 2324-T39
Vertical tail skin	Composites*	Composites*	**7075-T6**	**7075-T6**	Composites*
Horizontal tail skins (upper)	Composites*	Composites*	**2024-T3**	**2024-T3**	Composites*
Horizontal tail skins (lower)	Composites*	Composites*	**7075-T6**	**7075-T6**	Composites*

* Composites vary but include materials such as epoxy, bismaleimide, polyimide, fibreglass, boron fibre, carbon fibre, and more recently carbon fibre reinforced plastic (CFRP).

Table 4.3 Alloy types used as external skin by common aircraft type. Alloys tested are in bold type. Table derived from Brady, 1999; NMAB 1996; Good, pers. comm., 2009, Starke & Staley 1996, Smith, (2003) AZoM, 2004.

While these alloys are usually covered with paint or pure aluminium cladding, testing them was necessary as the potential for exposure to ash leachates still exits. This could occur through scratches in cladding or paint, fastener holes, areas of peeled paint, door mechanisms/hinges etc. Bare alloy, clad alloy and painted sections of aluminium were tested. Two types of paint have been used on the painted samples tested; a white gloss isocyanate commonly found on commercial aircraft exteriors, and a green "corrosion inhibiting" matt primer. The rationale behind performing this work was to assist airport operators and aircraft engineers in making informed decisions on prioritising ash cleanup, and determining optimal cleaning methodologies for cleaning aircraft.

4.4.3.1 Methodology

Bare aluminium alloy, clad alloy and painted aircraft panels were divided into sections and photographed pre-testing, using both macro lenses and an optical microscope. Further imaging was conducted post testing using a scanning electron microscope.

The chemistry of ash leachates differs not just between volcanoes, but in different eruptions from the same volcano, or may even change during an eruption when the eruption style changes. There is because there are a large number of variables in determining volatile adsorption onto ash particles (Witham et. al., 2005). Cl, Ca, Na, SO_4^{2-}, Mg and F are commonly found in high concentrations in ash-water leachates are (IVHHN, 2005). Fresh ash and associated leachates were not available at the time of experimentation, however lahar samples taken from the September 2007 eruption of Mt Ruapehu provided good substitutes for volcanic ash leachates. These samples were collected from both the Whakapapa skifield and the Whangaehu river lahars. The Whangaehu river sample sediment was derived from the March 2007 lahar, the chemistry of the river water mixed with that sample was influenced by the September 2007 lahar. Samples were gathered at various distances from source, with corresponding changes in pH values. This provided a useful variety of samples to test on the aircraft aluminium, as their volcanic source meant that they were chemically good proxies for potential leachates. The slightly different physical nature of the wet lahar sediment meant that usual leachate analyses as described by Witham et al., (2005) were not appropriate in this case. An analysis of the composition of the sediment was conducted by Massey University's Fertilizer & Lime research centre. The lahar samples were found to be extremely high in sulphates; SO_4 was measured at between 2190 and 2623 μg/g of sediment. High sulphate levels are typical of ash leachates (Witham et al., 2005)

Three different wet sediment samples were used in testing. The sample collected from the Whakapapa lahar had a measured pH of 2.5, the pH of the Whangaehu samples were 3.4 and 4.5 respectively. Each of these samples were applied to both bare aircraft alloy and painted aircraft panels (figure 4.7).

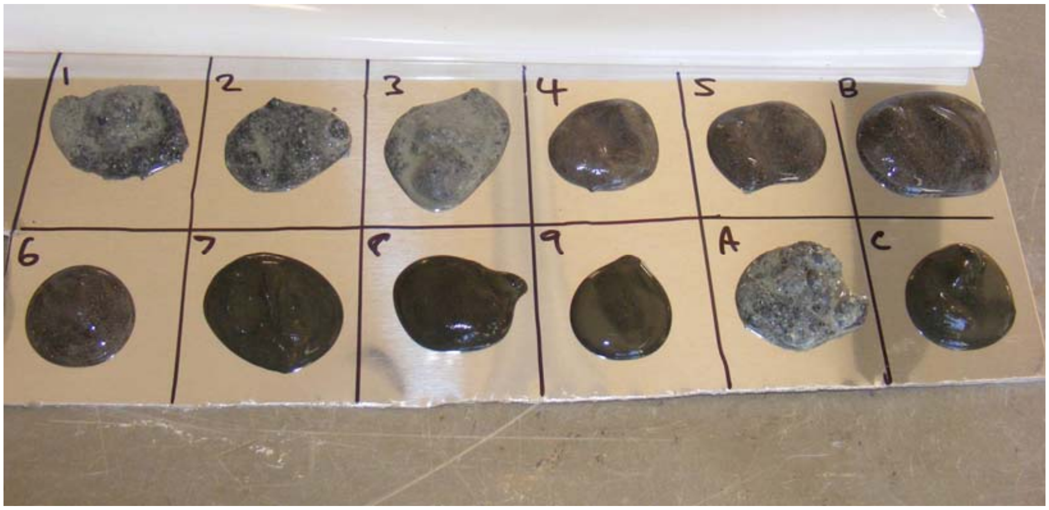

Figure 4.7: Wet ash samples applied to 7075-T6 alloy

Samples were left undisturbed on the surfaces for 6, 24, 48 or 96 hours. Sediment was wiped off with a soft dry cloth at the end of each test period. In all cases the samples required more pressure to remove after 24 hours had elapsed than following the 6 hour tests. A dry ash test was also conducted on all bare sample types. This sample came from the same Whakapapa lahar source as the sample used in leachate testing, but was unsealed and allowed to dry at room temperature for 3 days. It's pH was subsequently measured at 2.9 (as opposed to 2.5 for the wet sample), but this reading should be treated with caution due to the dry nature of the sediment.

Further testing of the potential for ash abrading surfaces during clean up involved leaving ash on sections of clad aluminium and painted aluminium. As abrasion testing required an actual ash sample rather than lahar sediment to give accurate results, ash from the 1994 Rabaul eruption was used. This dacitic ash had a mean grainsize of 88.9 μm and a modal grainsize of 79.6 μm. Prior to application it was mixed with acidic Whangaehu river water that had been sampled several hours after the September 2007 lahar. After buffering the pH of the ash-water mix remained at 3.7. This mix was then applied to both clad and painted alloy surfaces. Once the ash had been left on the surface for the required time (either 6, 24 or 48 hours), it was cleaned off using a brush, water, or a combination thereof, this is the most likely method to be used by airport maintenance staff. Vacuuming would not work on the ash, as having been wet it strongly adhered to the surfaces once dried. Compressed air would be impractical and largely ineffective on the slightly cemented ash.

4.4.3.2 Results

Corrosion testing

Tables 4.4- 4.9 indicate the results of ash leachate corrosion tests on aircraft surfaces. SEM micrographs of pitting on tested surfaces after being exposed to a leachate of pH 2.5 for 24 hours are included for comparison.

Rare pitting:	Pits constitute <1% of the surface area
Minor pitting:	Pits constitute 1-5 % of the surface area
Pitting:	Pits constitute 5-10 % of the surface area
Extensive pitting:	Pits constitute >10% of the surface area.

Impacts of ash leachates on unclad 7075-T6 alloy		
pH	**Exposure duration (hours)**	**Observations**
2.5	6	Mild oxidation on surface, minor pitting 10-30 µm deep
2.5	24	Significant surface oxidation, pitting 10-30 µm deep
2.5	48	Significant surface oxidation, extensive pitting 10-30 µm deep
2.5	96	Significant surface oxidation, extensive pitting 10-30 µm deep
3.4	6	Very mild oxidation on surface, rare pitting 10-30 µm deep
3.4	24	surface oxidation, pitting 10-30 µm deep
3.4	48	Significant surface oxidation, extensive pitting 10-30 µm deep
3.4	96	Significant surface oxidation, extensive pitting 10-30 µm deep
4.5	6	Slight discolouration of surface
4.5	24	Very mild oxidation on surface, rare pitting
4.5	48	Very mild oxidation on surface, rare pitting
4.5	96	Very mild oxidation on surface, rare pitting

Table 4.4 Impacts of ash leachates on unclad 7075-T6 alloy

Impacts of ash leachates on unclad 2024-T3 alloy		
pH	**Exposure duration (hours)**	**Observations**
2.5	6	Mild oxidation on surface, pitting
2.5	24	surface oxidation, pitting 10- 30 µm deep
2.5	48	Significant surface oxidation, pitting 10- 30 µm deep
2.5	96	Significant surface oxidation, pitting 10- 30 µm deep
3.4	6	Slight oxidation of surface, minor pitting 10- 30 µm deep
3.4	24	Surface oxidation, minor pitting < 10 µm deep
3.4	48	Surface oxidation, minor pitting < 10 µm deep
3.4	96	Surface oxidation, minor pitting < 10 µm deep
4.5	6	Rare slight pitting, negligible oxidation except on edges of area exposed to leachate where a slightly more oxidised rim exists
4.5	24	Very mild oxidation on surface, rare pitting < 10 µm deep
4.5	48	Very mild oxidation on surface, rare pitting < 10 µm deep
4.5	96	Very mild oxidation on surface, rare pitting < 10 µm deep

Table 4.5 Impacts of ash leachates on unclad 2024-T3 alloy

Impacts of ash leachates on clad 2024-T3 alloy		
pH	**Exposure duration (hours)**	**Observations**
2.5	6	Minor oxidation, rare pitting
2.5	24	Significant surface oxidation, minor pitting 10-50 µm deep
2.5	48	Significant surface oxidation, pitting 10-50 µm deep
3.4	6	Very minor areas of oxidation, no pitting
3.4	24	Surface oxidation, rare pitting 10-30 µm deep
3.4	48	Significant surface oxidation, rare pitting 10-30 µm deep
4.5	6	No discernable impact
4.5	24	Minor oxidation, no evidence of pitting
4.5	48	Minor oxidation, no evidence of pitting

Table 4.6 Impacts of ash leachates on clad 2024-T3 alloy

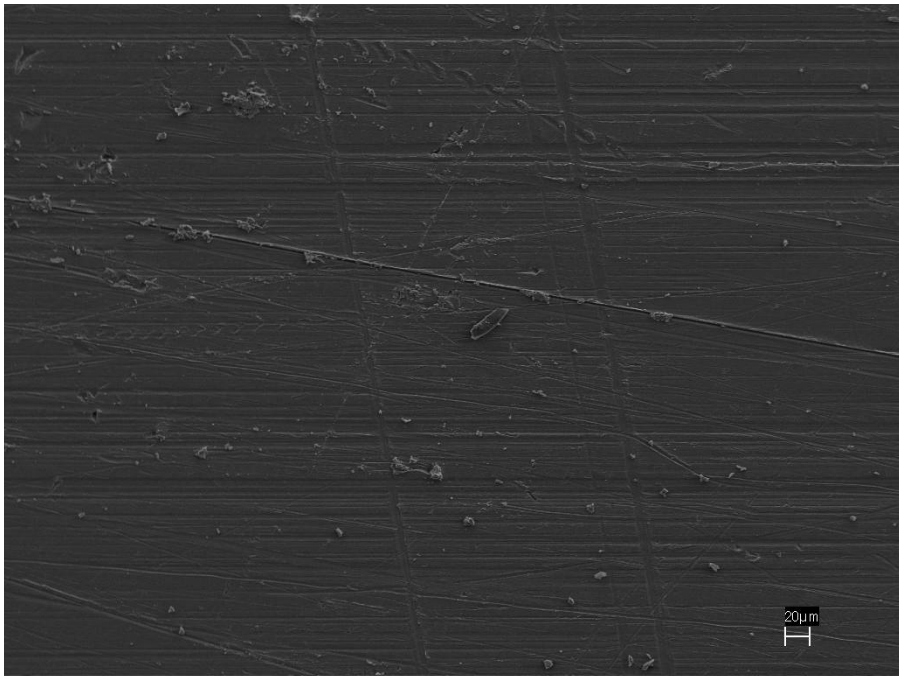

Figure 4.8 SEM micrograph of surface of clad 2024-T3 aluminium prior to testing. Small amounts of dust are present. Fine scratches such as the prominent one pictured on a diagonal are not uncommon. Faint grooves running across the surface left to right are part of the manufacturing process.

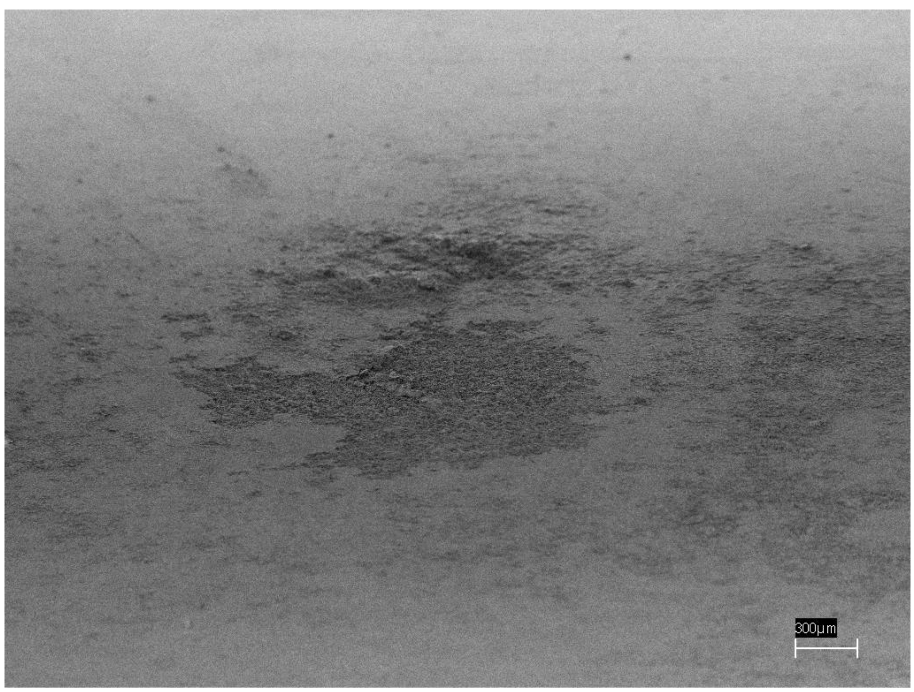

Figure 4.9: SEM micrograph of 7075-T6 aluminium after being exposed to a leachate of pH 2.5 for 24 hours (note larger scale than figures 4.8 and 4.10)

Figure 4.10: SEM micrograph of 7075-T6 aluminium after being exposed to a leachate of pH 2.5 for 24 hours.

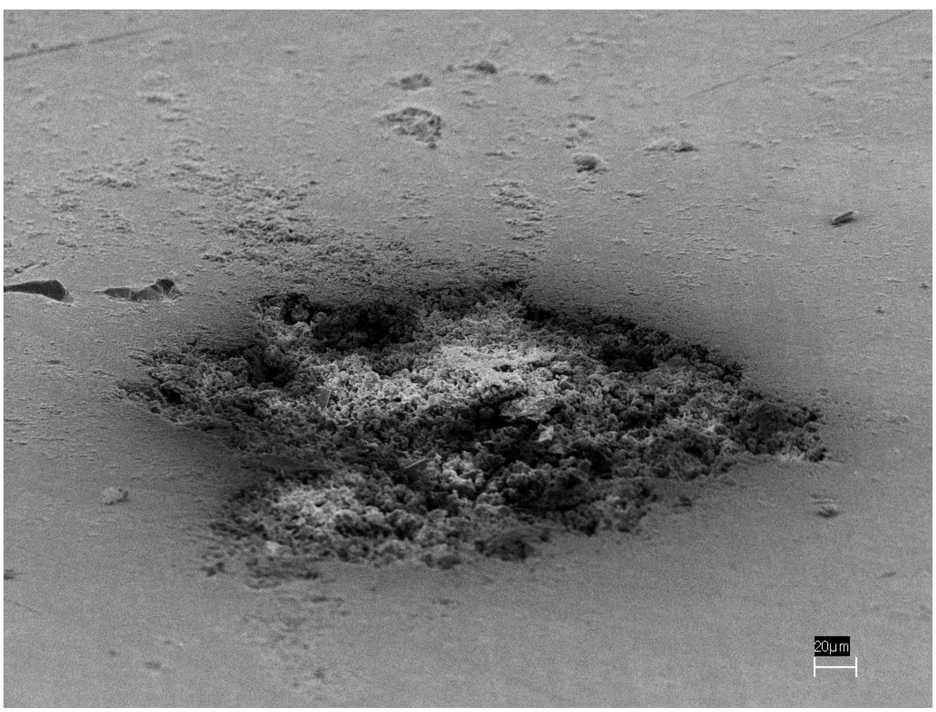

Figure 4.11: SEM micrograph of 2024-T3 aluminium after being exposed to a leachate of pH 2.5 for 24 hours

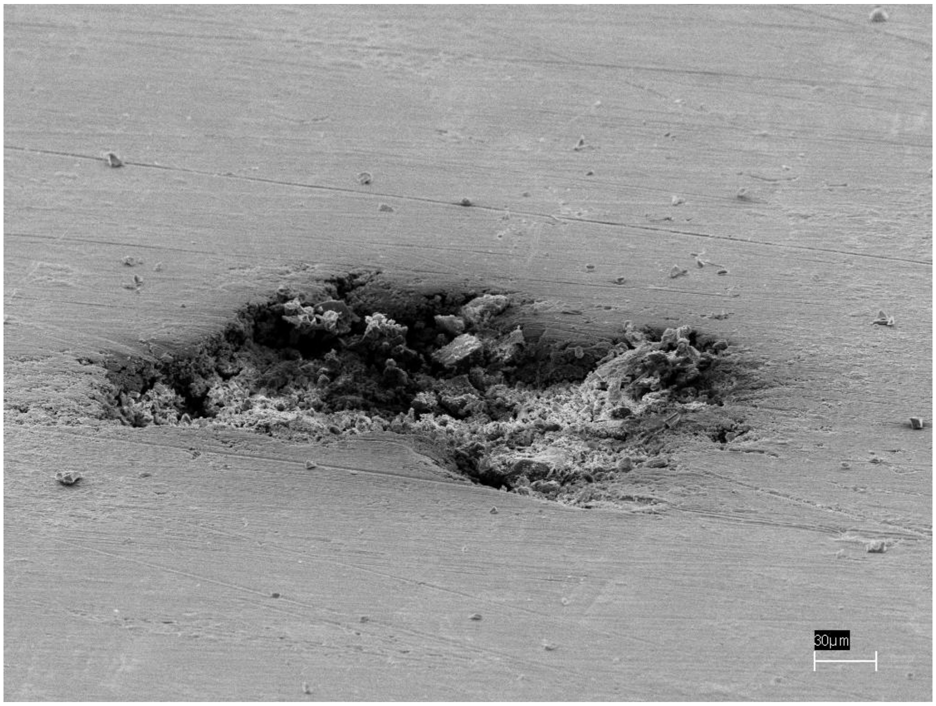

Figure 4.12: SEM micrograph of clad 2024-T3 aluminium after being exposed to a leachate of pH 2.5 for 24 hours

Figure 4.13: Optical Microscope view of 2024-T3 aluminium after being exposed to a leachate of pH 2.5 for 24 hours. The oxidised surface (lower ¾ of image) clearly stands out against the untested surface. Note pitting. Field of view is 8 mm.

Impacts of ash leachates on painted aircraft surfaces (glossy isocyanate)		
pH	**Exposure duration (hours)**	**Observations**
2.5	6	No observed effect
2.5	24	Little effect, minor ash adherence to surface, easily removed with cloth
2.5	48	Increased ash adherence to outside of sample area, no other effect apparent
2.5	96	Increased ash adherence to outside of sample area, no other effect apparent
3.4	6	Increased ash adherence to outside of sample area, no other effect apparent
3.4	24	Increased ash adherence to outside of sample area, no other effect apparent
3.4	48	Increased ash adherence to outside of sample area, no other effect apparent
3.4	96	Increased ash adherence to outside of sample area, no other effect apparent
4.5	6	Increased ash adherence to outside of sample area. no other effect apparent
4.5	24	Increased ash adherence to outside of sample area. no other effect apparent
4.5	48	Increased ash adherence to outside of sample area. no other effect apparent
4.5	96	Increased ash adherence to outside of sample area. no other effect apparent

Table 4.7 Impacts of ash leachates on painted aircraft surfaces (glossy isocyanate)

Impacts of ash leachates on painted aircraft surfaces (matt primer)		
pH	**Exposure duration (hours)**	**Observations**
2.5	6	Increased ash adherence to outside of sample area. no other effect apparent
2.5	24	Increased ash adherence to outside of sample area. no other effect apparent
2.5	48	Increased ash adherence to outside of sample area. no other effect apparent
2.5	96	Increased ash adherence to outside of sample area. no other effect apparent
3.4	6	Increased ash adherence to outside of sample area. no other effect apparent
3.4	24	Increased ash adherence to outside of sample area. no other effect apparent
3.4	48	Increased ash adherence to outside of sample area. no other effect apparent
3.4	96	Increased ash adherence to outside of sample area. no other effect apparent
4.5	6	Increased ash adherence to outside of sample area. no other effect apparent
4.5	24	Increased ash adherence to outside of sample area. no other effect apparent
4.5	48	Increased ash adherence to outside of sample area. no other effect apparent
4.5	96	Increased ash adherence to outside of sample area. no other effect apparent

Table 4.8 Impacts of ash leachates on painted aircraft surfaces (matt primer)

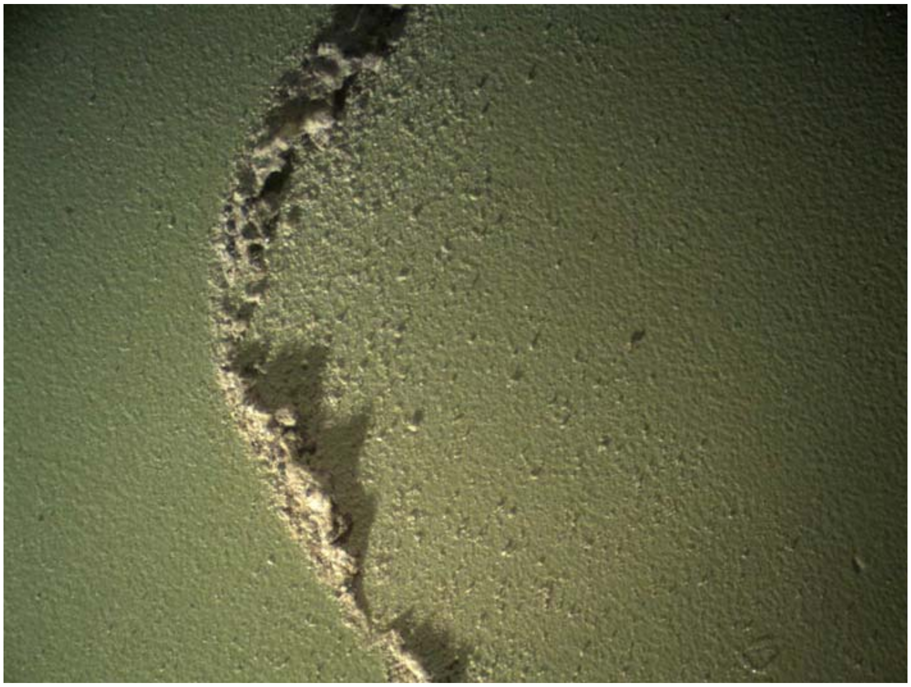

Figure 4.14: Painted Aluminium surface (matt primer) The surface on the left hand side of the ash has not been exposed to leachates, the right hand side has been exposed to a leachate of pH 2.5 for 96 hours. No effects were seen. Field of view is 13 mm

Impacts of dry ash (pH 2.9) on several aircraft surfaces		
Surface type	Duration (hours)	Observations
2024-T3 alloy	6	No effect, ash easily wiped off with cloth or brush
2024-T3 alloy	48	No effect, ash easily wiped off with cloth or brush
2024-T3 alloy	24	No effect, ash easily wiped off with cloth or brush
2024-T3 alloy	96	No effect, ash easily wiped off with cloth or brush
7075-T6 alloy	6	No effect, ash easily wiped off with cloth or brush
7075-T6 alloy	24	No effect, ash easily wiped off with cloth or brush
7075-T6 alloy	48	No effect, ash easily wiped off with cloth or brush
7075-T6 alloy	96	No effect, ash easily wiped off with cloth or brush
Clad 2024-T3 alloy	6	No effect, ash easily wiped off with cloth or brush
Clad 2024-T3 alloy	24	No effect, ash easily wiped off with cloth or brush
Clad 2024-T3 alloy	48	No effect, ash easily wiped off with cloth or brush
Clad 2024-T3 alloy	96	No effect, ash easily wiped off with cloth or brush
Painted* alloy	6	No effect, ash easily wiped off with cloth or brush
Painted* alloy	24	No effect, ash easily wiped off with cloth or brush
Painted* alloy	48	No effect, ash easily wiped off with cloth or brush
Painted* alloy	96	No effect, ash easily wiped off with cloth or brush

*Painted alloy surfaces tested were painted with glossy isocyanate.

Table 4.9 Impacts of dry ash on different aircraft surfaces

The results of these tests indicate that painted aircraft surfaces have adequate corrosion protection from volcanic ash leachates when covered by either primer paints or top coats. No damage to paint or discolouration occurred in this time frame. Conversely, unpainted aircraft surfaces were found to potentially be at substantial risk from corrosive acidic leachates. The effects of acidic leachates on bare surfaces were quickly apparent; in most cases significant oxidation had taken place on unpainted surfaces by the time ash was removed after 6 hours. Oxidation was clearly visible as a rough frosted type surface. It occurred on both clad and unclad alloys exposed to leachates equal to or more acidic than pH 3.4. The less acidic leachate (pH 4.5) had no discernable effect in this timeframe on aluminium clad alloy, and only slight impacts on unclad alloys. Oxidation increased over time though, and even the leachates with a comparatively benign pH of 4.5 caused some damage after 24 or 48 hours. By 48 hours after application the reaction between the acids and aluminium/alloy appeared to have ceased, no further effects were noted in the 96 hour tests.

As well as surface oxidation, all bare surfaces were found to be subject to pitting. Clad surfaces suffered from deeper pitting than the unclad alloys, due to the preferential electrochemical dissolution of the anodic pure aluminium cladding over the cathodic alloy. In most instances pit depth on clad alloys was 10 – 50 µm, whereas maximum pit depth on unclad alloys appeared to be ~30 µm (figures 4.8-4.12). While pitting on clad surfaces appeared to be deeper than on alloy surfaces, the total surface area affected by pitting was slightly higher on the 7075 alloy than the 2024 alloy. The pure aluminium cladding had a marginally smaller pitted surface area despite the deeper pits.

Despite their high acidity, without water acting as an electrolyte the dry ash did not affect aircraft surfaces. Even after 48 hours there was no impact on any of the bare or painted surfaces tested.

Abrasion by cleaning method tests

Removal of previously wet ash from clad 2024-T3 surface by cleaning method		
Method	Time until ash removed (hours)	Observations
Brushing/sweeping	6	Most ash easily brushed off except for residual ash which required low pressure water
Brushing/sweeping	24	Hard to remove, several passes with brush required to remove ash. Residual ash required low pressure water to remove
Brushing/sweeping	48	Not possible to remove without low pressure water aiding sweeping
Wetting	6	Easily rinsed off with low pressure water
Wetting	24	Most ash removed by water, muddy residue also required brushing
Wetting	48	Most ash removed by water, muddy residue also required brushing

Table 4.10 Removal of previously wet ash from clad surfaces by brushing/wetting.

Removal of ash from painted (glossy) surface by cleaning method		
Method	Time until ash removed (hours)	Observations
Brushing/sweeping	6	Ash easily brushed off, small areas of adherence were wetted to facilitate removal
Brushing/sweeping	24	Harder to remove, several passes with brush required to remove ash. Residual ash required low pressure water to remove
Brushing/sweeping	48	Harder to remove, several passes with brush required to remove ash. Residual ash required low pressure water to remove
Wetting	6	Easily rinsed off with low pressure water
Wetting	24	Most ash removed by water, muddy residue also required brushing
Wetting	48	Most ash removed by water, muddy residue also required brushing

Table 4.10 Removal of previously wet ash from painted aircraft surfaces by brushing/wetting.

Cleaning ash off surfaces with water and/or brushes was thought to have the potential to abrade paint or aluminium. This did not occur during these tests, both optical microscopy and SEM micrographs indicating negligible scratching or gouging on either aluminium clad or painted surfaces.

4.4.3.3 Implications of testing

Impacts to metal surfaces depend not just on the pH and the duration that ash is left on the aircraft, but on the presence of rainfall during or after ashfall. Testing indicated dry ash had no effect on any kind of aircraft surface, but wet ash resulted in leachates corroding and oxidising both clad and unclad surfaces. This means that light rain during or after ashfall could result in significant damage to ash covered aircraft. Heavy rain is likely to clean aircraft of ash, and is thus less of a problem in terms of corrosion. Wet ash from phreatic or phreatomagmatic eruptions will have the capacity to begin to cause corrosion immediately upon landing on the aircraft. As it is unlikely that leachate pH will be known immediately after ashfall, it will be necessary to treat any ash as being highly acidic, removing it from aircraft as soon as possible to prevent corrosion.

The amount of surface oxidation and pitting corrosion experienced in these tests would not in itself prevent aircraft flying. Oxidation of aluminium and alloy surfaces is common on aircraft; repairing oxidised surfaces is dealt with as part of routine aircraft maintenance and does not require immediate attention. Pitting is more serious, as once pits form they tend to continue to slowly grow over time. This type of corrosion therefore requires prompt attention. In the short term the mechanical performance of clad alloy is unlikely to be compromised by the level of pitting seen in these tests, as it is the clad surface that is corroded rather than the structural alloy. Pitting directly in alloy is more problematic, in that even aircraft skins are structural; pits can eventually lead to fatigue failure if they are located in a critical load path (Banis et al., 1999). The 10-30 µm deep pits experienced by the unclad 2024 and 7075 alloys amounted to between 1 and 3% of the 1 mm alloy thickness. This level of pitting is not sufficient to compromise the structural integrity of the alloy (D. Good, pers. comm., 2009). The corrosion does however need to be quickly removed, and the surface repaired. Depending on the extent of corrosion this could result in the aircraft being out of service for days to weeks. Even without this damage occurring, any aircraft subjected to ashfall will require extensive inspection to ensure all ash is removed and the plane is safe to fly.

The potential for abrasion while cleaning ash off aircraft surfaces exists, despite negligible abrasion occurring during testing. Different ash types may give different results. The ash used in testing was a fine grained dacite, its high silica content and angular grain shape made this a very abrasive ash. However volcanic ash could potentially be more abrasive than this, and give less benign results. This could occur with a more silicic rhyolitic ash, or even a glassy ash with sharp angular grains. Extreme care should therefore be taken when removing ash from aircraft skins. Abrasion to windshields and windows was not tested, as experience after the Pinatubo eruption suggests these can easily be scratched if rubbed when removing ash (Casadevall, 1992). Ideally windshields should be covered in the event of an aircraft being parked outside during an ashfall (figure 4.15).

Figure 4.15: TAME airlines Boeing 727-134 with improvised covers on windscreen, wheel assemblies and engine intakes

4.5 Summary of Potential Ashfall Impacts on Grounded Aircraft

While ash has landed on airports on more than 73 occasions since 1944, in most instances grounded aircraft were not impacted, often because they were moved in time to avoid the ashfall. Those impacts that have occurred include impact damage from larger clasts (bombs), charring from hot ash, tephra loading causing planes to rock back onto their tails, windscreen abrasion from incorrect cleaning and economic damage from taking aircraft out of service while they are cleaned and or repaired. These potential impacts still exist, as does the potential for corrosion and abrasion.

Testing of ash leachates on aircraft skins has shown the risk of corrosion to be a significant threat. Wet ash has the capacity to start attacking exposed metal surfaces immediately, causing pitting damage evident after just 6 hours, and extensive after 24 hours. This means aircraft need to be cleaned as soon as possible after wet ash lands on aircraft, or ash on aircraft becomes wet from rainfall. Abrasion is certainly a potential problem for windshield and windows, and remains a possibility on metal surfaces. Any moving part has the potential to be affected by abrasion, which is why covering vulnerable parts like wheel assemblies, windshields and engine intakes has been recommended practice for several years (e.g. Casadevall, 1993) More detailed methodologies for cleaning aircraft after ashfall are given by Labadie (1994) and repeated in ICAO (2001).

4.6 Mitigating the effects of ashfall on airports and grounded aircraft

The following series of recommendations for actions to take pre-event, during a volcanic eruption and after ashfall has ceased is derived from the experiences of Mariscal Sucre and Fontanarossa airports, results of laboratory tests, and previous recommendations (Casadevall (1993), Labadie (1994) and ICAO (2001)) based on eruptions over the last 30 years.

4.6.1 Pre-event.

Ideally these actions should be taken by any airport potentially subject to volcanic ash. At the very least they should be taken when warning of a possible eruption is given by the relevant authority (in New Zealand this is GNS Science).

- Acquire and store materials needed for covering or sealing openings and vulnerable areas on aircraft (engine and APU intakes, windscreens, nose cones, wheel assemblies, pitot tubes). Coverings for ground equipment such as electronic or computer equipment will also be required. These coverings can be as simple as duct-tape and plastic sheeting.
- Acquire and store additional cleaning materials (brooms, vacuum cleaners, cleaning fluids), dust masks and goggles for all staff on site, spare parts for essential machinery, oil filters, air filters, lubricants.
- Prearrange additional means of cleaning paved areas, runways etc. This may involve agreements for the hire of street sweeper trucks, water tankers, front end loaders, rollers etc, or arrangements with contractors
- Prearrange a source of auxiliary power generators.
- Prearrange a source of large volumes of water for cleaning up volcanic ash
- Locate areas suitable for temporarily or permanently storing volcanic ash once it has been removed from the airport.

Once an eruption appears imminent these additional measures should be undertaken

- Cover exposed equipment (especially computer or electronic equipment) with plastic sheeting
- Put any other equipment not in frequent use inside buildings
- Supply water hoses to the temporary ash storage area
- Any aircraft not evacuated from the area before ashfall should have the following areas or components covered with plastic sheeting and tape: Engine and APU intakes, windscreens, nose cones, wheel assemblies, pitot tubes
- Aircraft with large horizontal tails may accumulate large amounts of ash and rotate backwards about the rear wheels onto their tails. These need to be supported or anchored as appropriate.

4.6.2 During ashfall

- Move inside/cover any other equipment still outdoors
- Begin cleaning runways and taxiways with vacuum/sweeper trucks, or ploughs/blades as appropriate for the amount of ash.
- Clean other areas airside
- Wet the safety strips (green areas beside runway) and plough in ash with a pulvimixer, followed by a roller (light ashfall only).
- Thoroughly wet the ash storage area, keep water spraying over the ash.
- Clean ash from large span roofs (such as hangars) before more than ~5 cm has accumulated, to allow a generous safety margin before roof collapse. Slippery conditions mean all workers near edges should be harnessed.
- Clean damp or wet ash off exposed aircraft surfaces as soon as possible, concentrating on exposed metal surfaces

4.6.3 After the eruption has ended

- Clean elevated surfaces (balconies, roofs, canopies etc).
- Complete runway/taxiway cleaning
- Complete aircraft cleaning
- Uncover equipment that has been covered up

- Continue to wet safety strips beside runways
- Remove ash from temporary storage area(s)
- Inspect runways/taxiways/aprons
- Resume normal airside operations
- Clean other areas (e.g. carparks).

4.6.4 Removing ash from airports

Experience at different airports in the past has shown that there are a number of methods that can be employed to clean up ash from runways/taxiways etc. Deposits thicker than a few millimetres deep can be bladed into lines using graders/snowploughs, this method was used at Fairchild Air Force Base after ashfall from Mount St Helens in 1980. The experience of Quito's Mariscal Sucre airport has shown that with a large enough workforce it is possible to remove several millimetres of ash with brooms and manual labour. The account of the use of vacuum/sweeper trucks and rollers employed to remove light ashfall from runways and other airside areas by SAC not only gives useful information about how to remove thin deposits of ash, but indications of the length of time it takes to perform such tasks. With this information plans for the required amount of machinery to resume operations in a given timeframe can be established. As most ashfall impacts on airports are light, and cheap readily available labour forces are not common, this method is likely to be the most commonly employed for removing ash from airports.

Methods for removing ash have not deviated greatly since those used after the 1980 Mt St Helens eruption, and detailed in ICAO document 9691 (2001). General principles remain the same, the methodologies employed by SAC in Catania reflect this, but have slightly refined the process through frequent experience. These refinements include beginning the cleaning process during ashfall, determining that running sweepers lengthways and water tankers widthways across runways works faster, and that a vacuum and sweeping combination works best on light ash deposits.

Suggested practices for mitigating the effects of volcanic ash are recommended for New Zealand, through the establishment of a preliminary response plan for volcanic ash for Auckland Airport and Air New Zealand. This plan is currently in preparation as a GNS Science report, and included in this thesis as appendix 2.

4.7 Summary

Provided aircraft are adequately protected, and roofs are cleaned before tephra loading becomes an issue, physical damage resulting from ashfall can be minimised. However impacts to airports and grounded aircraft are not only physical. Financial losses resulting from the costs of airport closure are likely to exceed those incurred from damage and cleanup. Pre planning for ashfall is essential to minimise airport closure time, facilitating a rapid return to business as usual. A reactive approach to ashfall will result in more damage and a longer recovery time, as access to required cleaning equipment (including runway cleaning machinery) may not be possible, contacting staff may be difficult, and aircraft may be stranded and unnecessarily exposed to ashfall. Even seemingly simple omissions like a shortage of personal protective equipment such as dust masks may hinder clean up procedures, ultimately costing more in airport closure time. The mitigation strategies listed in this chapter will aid the process of effectively managing the risk posed by volcanic ashfall.

CHAPTER 5: VEHICLE MOBILITY ON ASH COVERED ROADS.

5.1 Introduction

Recordings of ash affecting vehicles have largely concentrated on damage to vehicle components (e.g. Labadie, 1983), reports of lowered visibility whilst driving in ashfall (e.g. Blong 1984) and thin layers of ash making driving conditions slippery (e.g. Durand et al. 2001). This information is certainly valuable, but in planning for an evacuation or responding to an eruption, emergency managers also need to know whether it is possible to actually drive vehicles on ash covered roads. If so how much ash is it possible to drive through? Ideally roads will be cleaned by roading contactors or local authorities before vehicles commence driving on them, but this is not always possible or practical. Driving on ash covered roads may be necessary for evacuees from affected areas, emergency services, emergency responders, lifelines maintenance or repair staff and infrastructure/utility providers. Even getting road maintenance staff to depots to access road cleaning equipment may necessitate a vehicle journey on an ash covered road.

This chapter seeks to determine what depths of ash may prove difficult or impossible to drive through. This is based both on evidence from historical eruptions and from experiments undertaken on Mount Etna in 2002 and 2005. It should be stressed that this work is very much of a preliminary nature, and further research is required to more accurately determine the affects of ash on vehicles and vehicle mobility. In the context of there being very little information published on this subject, the small amount of work done here is indicative only.

5.2 Ashfall, roads and vehicles since 1980

1980: Mt St Helens: Ashfall on roads following the May 18 and subsequent eruptions of Mt St Helens resulted in reduced visibility, accidents, speed restrictions, stranded travellers and altered traffic volumes (Blong, 1984). Approximately 3000km of State Highways were closed for a week, thousands of county and municipal roads were closed for hours to weeks (Schuster, 1981). These roads were generally closed due to slippery conditions and visibility problems rather than by the inability of vehicles to get through, as layers of ash were usually thin enough to be driven on. The Yakima area received about 10-15 mm of ash, but further away Ritzville was impacted by 40 mm of ash (Blong, 1984). According to *The Columbian* newspaper (May 26 1980) some vehicles trying to leave Ritzville on the I-90 (12 out of 75 cars) turned back because of poor road conditions (Blong, 1984). It is not specified whether this was because of visibility, slipperiness, traction problems or driver caution.

1991 Mt Pinatubo: After the June 1991 eruption the Olangapo and Subic Bay city areas had to cope with 15-20cm of coarse ash on major roads (Nairn, 2002). This was cleared after 2 days by scraping it to the side of the road. More problematic were mudflows from slopes adjacent to roads and flooding as drains became blocked. Lahars also destroyed bridges (Nairn, 2002). Millimetres to centimetres of ash remained on roads for months as wind remobilised ash from piles on the side of the road.

1991 Mt Hudson: Vehicles in Perito Moreno were involved in accidents when driven through ashfall at moderate speeds. Engines suffered damage and caused vehicle breakdown, due mainly to air-filter and carburettor blockages (Bitschene, 1995).

1992 Mt Spurr: The August 18th eruption deposited about 3 mm of ash on Anchorage. Roads were affected in that visibility was reduced, however rainfall on the evening of the 19th alleviated the problem. City buses stopped operating on the 18th, and ran a limited service on the 19th. Increased maintenance of vehicle fleets was reported to have been necessary for many organisations (Johnston, 1997b).

1992 Mt Unzen: Reduced visibility on roads was reported following the Mt Unzen eruption (Yanagi et al. 1992).

1994 Tavurvur and Vulcan, Rabaul: The Rabaul eruption provides a unique example of thick ashfall covering an urban area in modern times. Up to 1 metre of primary ashfall from both cones (Tavurvur and Vulcan) covered the township. The roads in Rabaul are laid out in a grid pattern North-South and East-West. Most of those roads have a constant gradient of 2 - 5% between the caldera wall and the harbour (SMEC, 1999). These could be driven on when dry (Nairn, 2002), but became slippery after a small amount of rainfall. This led to roads becoming impassable to all but four wheel drive vehicles – and even these were often stuck as vehicles sunk into the thick ash deposits (Stammers, 2000). Stuck vehicles were especially an issue in the wet season, as increased runoff after rainfall and the presence of a great volume of ash meant mudflows were common and further blocked roads (Nairn, 2002; Blong & McKee, 1995).

1995-96 Mt Ruapehu: Thin layers of ash deposited over the central and eastern North Island caused slippery road conditions after the 1995 and 1996 Ruapehu eruptions. During the 1995 eruption the Desert Road (SH1) was closed 3 times as a result of both ashfall causing reduced visibility, and an ash and rain mix making a slippery sludge that was deemed to be to dangerous for the road to remain open (Johnston, 1997a).

2002 El Reventador: On November 4, 2002 2-5 mm of ash covered Quito, following the eruption of El Reventador (Leonard et al., 2005). Vehicle circulation in the city was reported to have been banned, except for emergencies (PAHO/WHO, 2002). On following days most drivers were said to have driven cautiously – ashfall is not uncommon in Quito so most drivers had some experience driving on slippery ash and dealing with obscured road markings. Vehicle damage was minimal; some vehicles were reported to have minor problems with ash getting into fuel injectors and carburettors as small amounts of ash managed to get through the air filter. These problems were easily rectified with regular maintenance of vehicles. Some windscreens were scratched by wiper blades when used to remove ash (Leonard et al., 2005).

2002 Mt Etna: The 2002 eruption of Mt Etna, while sizable compared to previous recent activity nevertheless created havoc on local roads in Catania, even with less than 2 mm of ash covering roads. Numerous traffic accidents occurred, due to the slippery conditions and increased stopping distances. Falls from motorcycles and scooters/mopeds were so common that for a short time after the eruption riding them was banned in Catania. Public outcry soon reversed this decision (Barnard, 2004). Steep hills became difficult to climb for 2 wheel drive vehicles, even with thin (~2 mm) coverings of ash. Only drivers with determination and a willingness to slowly advance uphill while spinning tyres were observed to make it up some hills in urban areas on the flanks of the volcano. The spinning tyres would remove ash as the vehicle progressed, allowing it to grip the asphalt beneath. This was more of an issue for front wheel drive cars (which represent the majority of cars locally). The weight distribution of a vehicle driving uphill is transferred to the rear, causing the front wheels to lose traction on slippery surfaces. This was observed in both wet and dry conditions.

1955 – Present Day Sakurajima: Ashfall from Sakurajima volcano has periodically fallen on Kagoshima city since the present active period began in 1955 (Nairn, 2002). The main issue for roads and transportation is ash covering road markings and creating a slippery surface. This occurs with any ashfall greater than 1 mm depth (Durand et al, 2001). Ashfall does not usually exceed a few millimetres thickness – it has only exceeded 5 mm on four to five occasions (Lorden, 2001). Kagoshima City attempts to clean up ashfall within 3 days, using a combination of road, footpath and hand sweepers. Failure to do so can result in ash "setting" and becoming more difficult to remove (Durand et al, 2001).

5.2.1 Summary:

The reports referenced above generally refer to situations involving thin layers of ash affecting roads. Impacts include reduced visibility, slippery conditions, covered road markings, and increased maintenance requirements on vehicles. As these examples imply, in the well known volcanic events of the last 30 years few eruptions have affected road networks with more than a few centimetres of ash – Rabaul is the obvious exception here. When it comes to driving on thicker deposits of ash, or even driving on slopes that are covered with ash, a whole different set of problems emerge – being able to actually move vehicles. There are a large number of variables in both ash type and vehicle type/configuration affecting how possible this is.

5.3 Variables affecting mobility on ash covered roads:

5.3.1 Variables in vehicles affecting mobility on ash covered roads:

- **Drive:** Front wheel drive/rear wheel drive/four wheel drive. Four wheel drive will naturally provide the most traction.
- **Tyres:** Tread pattern, tread depth, tyre width, tyre circumference, tyre inflation. Off-road mud tyres with a deep tread pattern have an advantage in keeping vehicles moving on uneven surfaces or in wet muddy type conditions. However normal road tyres often perform well driving on sandy surfaces, these will usually perform just as well when driving on the top of thick amounts of ash on flat terrain – they don't dig in as much as mud tyres, and may thus help forward momentum. Large circumference tyres are advantageous when crossing ruts. Tyre width, (also affected by tyre inflation) will have an impact on how much vehicles sink into ash. Wider tyres increase the vehicle footprint – spreading the weight over a larger area so that it doesn't sink as much. Lowering tyre pressure, (a common 4wd technique) will also widen the footprint of the tyre and help prevent vehicles bogging down in ash. 10psi is sufficient for driving on sandy (and thus ash) surfaces, but not for driving on tar seal.
- **Weight:** Overall weight of the vehicle plus weight distribution. Heavier vehicles need more torque to keep moving in thick ash deposits as they will sink further. Where the weight is distributed on a vehicle will have an impact on wheel traction. For example a rear-wheel-drive front-engine car will generally have less traction on ash covered surfaces than a front-wheel drive front-engine car due to the weight of the engine being at the opposite end of the car to the driven wheels. This is applicable to maintaining forward movement, not braking or turning on thin slippery deposits.
- **Power & torque:** Torque is more important than horsepower in keeping vehicles moving in thick unconsolidated deposits – similar to vehicles bogged in mud.
- **Ground clearance:** This is only an issue in deeper or rutted ash where vehicles may sink into the deposit and become "bogged".

- **Differential type:** Open, locked or limited slip. With an open (normal) differential only one wheel needs to be stuck or spinning to prevent the vehicle from moving any further. With a limited slip or locked differential power will still be delivered to the other wheel(s).
- **Traction control system (TCS)** The presence of this feature enables some vehicles to eliminate wheel spin by cutting power or applying brakes to one or more wheels. The exact computer settings and configuration of the system will influence how much wheel spin occurs, or how much the vehicle slips if driving on thin slippery deposits.
- **Transmission:** manual or automatic. Automatic gearboxes generally deliver power more smoothly and result in less wheel spin, improving traction.
- **Driving style:** How the driver approaches driving. Experienced off-road drivers may have an advantage in keeping forward momentum driving on surfaces covered in thick ash. Sudden or jerky acceleration is more likely to result in a loss of traction than the smooth application of power.

5.3.2 Variables in ash affecting mobility on ash covered roads:

- **Depth:** Thin layers of ash (up to a few millimetres) are slippery, and may result in accidents if driven on too quickly. A few (>5) millimetres of ash may result in traction problems for two wheel drive vehicles when driving uphill on unconsolidated fine ash, but slow progress may be made on tar-seal as tyres spin and remove ash, exposing the road surface beneath.
- **Grainsize:** Fine ash is more problematic when wet than coarse ash, turning into a muddy slurry that can easily bog vehicles. An analogy is wet sand compared to mud. Wet sand may support the weight of a vehicle where mud does not.
- **Water content:** Most reports of slippery conditions after ashfall refer to wet ash, however thin coverings of ash will be slippery whether wet or dry. Once thicknesses are above a few millimetres the dynamics change, and with enough water a slurry may form, which may bog vehicles.
- **Degree of compaction or cementation:** Loose unconsolidated ash is the most problematic, as vehicles will sink into it. An ash deposit that has compacted

over time, or even undergone a degree of cementation after rainfall may be able to be driven on in the same way as sand may be driven on. Similar dangers to driving on beaches or in deserts will exist in terms of patches of less consolidated sand/ash which may cause vehicles to become stuck.

- **Smooth vs. rutted:** Smooth surfaces provide less resistance than rutted surfaces, allowing vehicles to progress more easily. However as more vehicles cross thick ash deposits more ruts will form.

5.3.3 Variables in road type affecting mobility on ash covered roads:

- **Slope of road:** The steeper the ash covered slope is the more difficult it is to climb. On flat roads thick deposits of fine-medium sand sized ash will in some circumstances be passable even to two wheel drive vehicles, but moderate slopes can become insurmountable barriers to the same vehicles.
- **Road surface:** Smooth tar-seal/coarse chip bitumen/gravel/dirt. These variables only apply where tyres have some contact with the road – i.e. in shallow coverings of ash or where wheel-spin removes sufficient ash for the tyres to reach the road surface. Coarse chip bitumen will afford the most traction.

5.3.4 Other issues

- **Drainage:** Culverts etc will likely become blocked with ash during/after rainfall. This may result in surface flooding on roads. This presents a whole new set of problems. Similarly ash may be remobilised by wind and create large drifts, or by rainfall on slopes adjacent to roads, causing muddy flows of ash onto roads. Runoff may also result in erosion of road surfaces.
- **Objects on Roads:** Trees, branches, power poles or lines downed because of ash loading may fall on roads and block or hinder progress. In extreme cases collapsed or partially collapsed buildings may also create obstacles.
- **Bridges:** Aside from the prospect of lahars destroying bridges, ash laden bridges may collapse, if sufficient load is applied. This is only likely in very thick ashfalls.

5.4 Driving on ash

Driving on ash can be likened to driving on sand, depending on the grainsize of the ash. There are differences between driving on a beach and driving on ash though. In most instances where attempts are made to drive through ash, deposits will tend to be thinner, the presence of a hard substrate (the road) beneath the ash will affect the potential progress of vehicles. Ash grainsize may differ from sand grains, which will also affect mobility

5.5 Experimental work: Driving in ash on and around Mount Etna.

5.5.1 Vehicles used in testing

Different vehicles were used to drive in ash conditions on Etna both during the 2002 eruption, and on remobilised (wind blown) ash around the Rifugia Sapienza area during 2005. The vehicles used on both occasions are recorded in table 5.1

Vehicle/model year	**Rear/front/4 wheel drive**	**Tyres**	**Other**
Toyota Prado (1998),	4wd	Road	Short wheel base
Fiat Panda (1994)	4wd	Road	Small wheels, narrow tyres
Toyota Hilux Utility (1999)	Rear	Mud	Note - 2wd
Toyota Prado (1998),	Rear	Road	(as 4wd but used in 2wd)
Fiat Stilo (2005),	Front	Road	Diesel
Nissan Micra (2002)	Front	Road	

Table 5.1: Vehicle and tyre type used in testing

The degree to which the vehicles coped with the ash conditions in 2002 was recorded, and a summary of results were first published in a brief table in 2004, reproduced below (Barnard, 2004).

Thickness of ash	Effects
0-2 mm	Road markings obscured, traction reduced (wet and dry ash), visibility reduced as dry ash is remobilized by traffic and wind. Steep hills difficult for 2wd vehicles to climb
2-20 mm	Moderate hills become difficult for 2wd vehicles to climb, steep hills impossible. Drifts cause larger humps in road. Once dampened and compacted it becomes firmer, easier to drive on.
20-100 mm	Slight inclines may be impassable to 2wd vehicles, 4wd vehicles may need closed (locked) differentials to climb moderate hills. Larger drifts (eg 300 mm) may hinder or stop 2wd vehicles on flat roads
100-300 mm	Uneven surfaces in the ash stop any 2wd vehicles, compacted damp ash on flat surfaces is still able to be driven on. 4wd utility type vehicles (not cars) may be able to slowly progress on the flat. Drifts may need to be cleared. Moderate inclines difficult, but may be possible for experienced 4wd drivers. Steep inclines generally impassable. Ruts easily formed on hills.
>300 mm	Compacted ash may be driven on by 4wd vehicles, softer patches may easily bog vehicles. Gradual inclines possible on compacted ash, but after a few vehicles ruts in the ash will form, hindering uphill progress for further vehicles

Table 5.2: Vehicle mobility on ash covered roads (Barnard, 2004).

Further work in 2005 has produced some modifications from the 2002 results. A more systematic approach was taken and a 2005 Fiat Stilo was used to attempt to drive through various thicknesses of ash on different slopes. This covered some variables that were not addressed in 2002. As the tests were conducted on the slopes of Etna, they were very close to the source of the ash. For this reason the grainsize of the ash was generally coarse. Furthermore the 2005 tests were conducted on remobilised wind-blown ash – the fine component had long since been removed by wind and rain. A sample of ash was taken from the moderate slope tests on 5-15 cm of ash with the Fiat Stilo. Results of a grainsize analysis conducted with a Micromeretics Saturn Digisizer 5200 indicated a coarse ash with a modal grainsize of 842.7 µm and a mean grainsize of 632.5 µm. Although different areas were used in testing, grainsize was similarly coarse in all of the 2005 tests.

The tests were also all conducted in dry conditions. As evidenced by reports from Rabaul the addition of water will make progress more difficult (SMEC international

1999). Unfortunately from this point of view rain was uncommon during the testing periods.

Results can only be taken as guidelines given the large amount of variables in both ash type and vehicle type/configuration. More systematic testing would be needed to establish a greater degree of accuracy, and quantitative results.

Ash thickness <5 mm (Dry)

Slope / **Vehicle**	**Flat or gently inclined (flat-1:17)**	**Moderate (~1:16-~1:10)**	**Steep (>1:10)**
Toyota Prado 4wd	Stopping distance increases.	Stopping distance increases.	Stopping distance increases, especially on decent. Uphill progress ok.
Fiat Panda 4wd	Stopping distance increases	Stopping distance increases	Stopping distance increases, especially on decent. Uphill progress ok.
Toyota Hilux rwd	Stopping distance increases	Stopping distance increases	Some loss of traction as ash cleared from beneath wheels. Slow progress uphill
Toyota Prado rwd	Stopping distance increases	Some wheel-spin on take off	Some loss of traction as ash cleared from beneath wheels. Slow progress uphill
Fiat Stilo fwd	Stopping distance increases	Some wheel-spin on take off	Loss of traction as ash cleared from beneath wheels. Slow progress uphill, wheel-spin.
Nissan Micra fwd	Stopping distance increases	Some wheel-spin on take off	Loss of traction as ash cleared from beneath wheels. Very slow progress uphill with almost constant wheel-spin.

Table 5.3: Vehicle Mobility on roads covered by less than 5 mm of dry ash

Ash thickness 5-15cm (Dry)

Slope / Vehicle	Flat or gently inclined (flat-1:17)	Moderate (~1:16-~1:10)	Steep (1:10 or steeper)
Toyota Prado 4wd	Progress slowed but otherwise fine	Progress slowed but otherwise fine	Progress slowed but otherwise fine
Fiat Panda 4wd	Progress slowed but still possible		Not tested
Toyota Hilux rwd	Progress slowed but otherwise fine	Progress slowed but still possible	Difficult to climb, but climb made with effort, and extra weight placed over back wheels.
Toyota Prado rwd	Progress slowed but otherwise fine	Progress slowed then 4wd engaged	Not tested in 2wd
Fiat Stilo fwd	Progress slowed (unconsolidated ash) but practical for short distances only.	Hill climbed with difficulty at walking pace. Possible to make progress but only practical for short distances. (unconsolidated ash).	Unsuccessful at climbing hill
Nissan Micra fwd	Not tested	Not tested	Not tested

Table 5.4: Vehicle Mobility on roads covered by 5 to 15 mm of dry ash

Figure 5.1: Fiat Stilo during testing on unconsolidated ash near Sapienza, Mt Etna

Figure 5.2: INGV Toyota Prado on ash Covered track on Mount Etna

Figure 5.3: INGV Fiat Pandas (as used in testing) parked on thin ash beside road, Monacella.

Ash thickness 20-30cm (Dry)

Slope / Vehicle	Flat or gently inclined (flat-1:17)	Moderate (~1:16-~1:10)	Steep (>1:10)
Toyota Prado 4wd	Can be driven on both unconsolidated and compacted ash (much more easily on compacted ash)	Compacted ash easily driven on, gradual uphill progress made on unconsolidated ash	Very slow uphill progress possible, it may take more than one attempt to climb. Ruts impede progress
Fiat Panda 4wd	Progress possible on compacted ash, not tested on unconsolidated ash	Progress possible on compacted ash, not tested on unconsolidated ash	Not tested
Toyota Hilux rwd	Progress possible on compacted ash, not tested on unconsolidated ash	Progress made on unconsolidated ash	Several attempts made at climbing a steep hill (~10 metres length) on an unconsolidated ash deposit. Successful only with weight placed over back wheels (with mud tyres) after several attempts had cleared some ash away with wheel-spin and run-up. Not advisable.
Toyota Prado rwd	Progress possible on compacted ash, not tested on unconsolidated ash	Not tested	Not tested
Fiat Stilo fwd	Progress possible on compacted ash, not tested on unconsolidated ash	Vehicle stuck	Vehicle stuck
Nissan Micra fwd	Not tested	Not tested	Not tested

Table 5.5: Vehicle Mobility on roads covered by 15 to 30 mm of dry ash

Ash thickness >30cm (Dry)

Slope / Vehicle	Flat or gently inclined (flat-1:17)	Moderate (~1:16-~1:10)	Steep (>1:10)
Toyota Prado 4wd	Can be driven on both unconsolidated and compacted ash (much more easily on compacted ash)	Compacted ash easily driven on, gradual uphill progress made on unconsolidated ash	Unsuccessful at climbing hill.
Fiat Panda 4wd	Progress possible on compacted ash, not tested on unconsolidated ash		Not tested
Toyota Hilux rwd	Progress possible on compacted ash, not tested on unconsolidated ash		Not tested
Toyota Prado rwd	Progress possible on compacted ash, not tested on unconsolidated ash	Not tested	Not tested
Fiat Stilo fwd	Not tested	Vehicle stuck, unsuccessful at climbing hill.	Vehicle stuck, unsuccessful at climbing hill.
Nissan Micra fwd	Not tested	Not tested	Not tested

Table 5.6: Vehicle Mobility on roads covered by over 30 mm of dry ash

5.6 Discussion

Driving on thin (less than a few millimetres) of ash is hazardous in that it is slippery, road markings are obscured and remobilised ash can cause severe visibility problems. This is indicated by experiences of drivers in recent historical eruptions, as well as research conducted around Mt Etna. However the traction problems associated with steep inclines in light ashfall conditions have previously not been documented. Other problems include driving during ashfall, where windscreens need to be frequently and carefully cleaned to avoid scratching them with wiper blades.

With more ash on the ground (a few centimetres) vehicle mobility issues become increasingly complex. These preliminary results indicate that two wheel drive vehicles begin to struggle even on moderate inclines as ash depths become greater than a few centimetres. It should still be possible for evacuees to use vehicles to leave affected areas, provided no steep hills are present. Even then it may be possible in some cases to slowly climb short hills covered in ash – e.g. to leave steep driveways to get onto cleared roads. However, given the amount of variables present this is not guaranteed; a shovel may still be necessary to clear a driveway in order to get a vehicle to the road in some situations. With this much ash or more around other complications could potentially occur. The weight of ash may have caused power lines, trees and branches to be downed across roads. Rain may cause culverts to become blocked, which would in turn cause localised flooding. Slips and mudflows from hilly areas adjacent to roads may also block progress for vehicles. Wind blown drifts of ash could cause further problems. By this stage utility companies and emergency responders should only consider using four wheel drive vehicles in hilly areas.

Once ash depths have exceeded 20cm it becomes impractical for two wheel drive vehicles to be used anywhere hills are present. While most vehicles may easily drive on compacted ash on flat surfaces, wheel-spin caused by cars negotiating hills will quickly cause ruts, which will in turn lead to vehicles becoming stuck. Even moving vehicles from where they are parked once this amount of ash is present will be difficult. Moderate inclines will impede four wheel drive vehicles, but is unlikely to stop them.

Over 30cm of ash causes similar problems, but to a greater degree. Four wheel drive vehicles will still be required to climb hills, but steep hills will not be passable to wheeled vehicles. (Tracked vehicles may be useful, but were not tested as part of this study). Further problems may include bridge loading of ash. Thick deposits may weaken or collapse bridges in extreme cases.

5.6.1 Driving on ash-covered roads in New Zealand

Should heavy ashfall impact New Zealand roads, it is unlikely that steep roads will need to be negotiated frequently. The typical maximum gradient for New Zealand state highways is 10% (1:10) (Transit NZ, 2002). There are some exceptions to this in mountainous terrain. Furthermore section 329 of the Local Government Act 1974 (no. 66) states: "*No road shall be laid out or constructed by the council, and no road or proposed road on any scheme plan shall be approved by the Council, with a grade in any part of its length steeper than...(clause c) one metre in 8 metres, in any case where that grade is not fixed by any such district scheme or by any bylaw or special order. In this section the term "road" does not include an access way"* Steep sections of road are therefore likely to be short, or driveways. These may be able to be cleared with shovels etc to enable vehicles to be used.

Where vehicles do drive on roads with more than a few millimetres of ash covering them carrying a shovel is advisable. A technique used by drivers stuck in sand is first to try to reverse out of the tracks made driving into the sand. If this doesn't work then digging away sand from the differential (usually the lowest part of the vehicle) may be necessary. Deflating the tyres to about 10 PSI is another technique used to help drive on sandy areas. Clearing tracks for the tyres can also help, as can gradually moving the vehicle back and forward in short steps.

5.7 Summary

Standard cars should be able to be used in light ashfall, by residents to evacuate from affected areas where up to a few centimetres of ash are present on the ground. The exact amount depends on the presence of hills and rainfall, as well as secondary problems affecting the roads (such as flooding, lahars, downed trees etc). Speed restrictions need to be in place to reduce the number of accidents caused by loss of traction and visibility. Once a few centimetres of ash cover roads they need to be closed to two wheel drive traffic except where used for evacuation. Over 15 to 20cm of ash will effectively block hilly areas to any two wheel drive traffic, and potentially stop them on the flat in some circumstances. Four wheel drive vehicles should be used by utility companies and emergency responders when ashfall has exceeded a few millimetres, if no other means of transport is available (e.g. helicopter/boat). They can be used on flat surfaces of compacted ash even at significant depths (i.e. 30 cm+), but may still become stuck, and should not travel alone. On steep inclines road vehicles of any sort will not be useable, and alternatives such as helicopters will need to be used – assuming airborne ash is not creating a hazard for aircraft. Tracked vehicles may be useful in some situations, but were not tested as part of this study

CHAPTER 6: WASTE WATER SYSTEMS AND VOLCANIC ASHFALL

6.1 Introduction

Serious volcanic ash impacts on wastewater systems are surprisingly rare. Few eruptions have deposited large amounts of volcanic ash (>10 mm) in urban areas at any one time, urban wastewater/stormwater systems have therefore not often been tested in terms of large quantities of volcanic ash entering the systems. In some of the few cases where this has occurred, contemporaneous processes like pyroclastic flows or lahars have taken place, destroying infrastructure to such an extent that impacts of ashfall alone cannot be determined (for example Rabaul, 1994) Where smaller amounts of ash have affected cities/towns, the effects of ash on their wastewater systems are rarely described.

Wastewater systems are distinct from storm water systems in that wastewater includes sewerage networks. Stormwater – rain runoff from built up areas is sometimes separated from wastewater, draining through its own reticulation network into natural drainage systems such as rivers, or directly into the sea. However stormwater and municipal sewerage networks often share reticulation systems, as the shared network of pipes requires less financial outlay at the time of construction. These combined wastewater systems allow for the ingress of ash into sewerage pipelines, as ash on the surface is carried by rainwater (or water used in clean up operations) into the stormwater system, and thus the sewerage reticulation network, eventually ending up at waste treatment plants. Failure of such systems will ultimately result in sewage backing up and overflowing into streets from drains and buildings from toilets. This in turn will cause a major health hazard.

6.2 Previous instances of ashfall affecting wastewater systems

6.2.1 Mt St Helens, USA, 1980

The effects of this eruption on the waste treatment plant in Yakima are to date the most well documented instance of this type of incident. This is thanks largely to a paper jointly written by the Wastewater Facilities Manager and the Process Control Supervisor at the Yakima Wastewater Collection and Treatment Facilities, Washington, (Day and Fisher 1980). The paper specifically described the effects of ash entering the treatment plant.

The city of Yakima, an area of 31km^2, was covered by about 10 mm of sand-sized ash on May 18 1980. The following account of the effects on the Yakima treatment plant is a synopsis of the Day & Fisher paper (1980).

In 1980 Yakima was served by a network of 446 km of wastewater lines; about 5% of these were combined stormwater and sewerage. The facility would normally process 69300m^3 of wastewater per day. Initially, during and immediately after the eruption on May 18th, the plant continued to operate largely as normal. The only change to normal procedure was that pH was closely monitored, and a drop from 6.7 to 5.7 was immediately noted; it is not recorded where in the plant this measurement was taken. Observations of ash reaching the plant were recorded on the following day, as 15 times the usual amount of sand and grit began to be received (but only partially removed) in the pre-treatment process. Throughout the day it became apparent that ash was damaging equipment, vibrations were occurring in grit classifiers and the gearbox of the mechanically cleaned bar screen. Pumping difficulties were experienced and sludge lines became blocked.

Two days after the eruption ash was passing throughout the system. Methane production was greatly reduced, biofilter media began to show bare patches. Sludge pumps – which were not moving sewage – were shut down at this point, as were the clarifier drive mechanisms.

By the third day biofilters had been stripped of almost all growth, the comminutor (sewage grinder) had completely failed, so was removed from the influent channel. Secondary treatment ceased, and by 9am the decision was made to bypass the treatment plant completely and pump sewage (after chlorination) directly into the Yakima River. A bypass and temporary chlorination facility was quickly constructed This took until the morning of Thursday May 22nd (day four).

By day five cleanup operations began – it was at this point that the sludge transfer pump failed, due to ash in the bearing grease which stripped the chromium coating of the bearings.

Eight days after the eruption, cleaning was initiated on the collection systems. This was performed using high pressure water and vacuum trucks - a method that was found to be effective. In total the cost of the repairs and cleanup was around $4 million (White et. al, 1980).

Yakima was not the only locality to have problems with ash in sewerage or stormwater systems. Moses Lake received 25 mm of ash, blocking stormwater drains and damaging the waste treatment plant sufficiently to render it inoperative (Schuster, 1981). With only 5 mm of ash in Spokane stormwater drains were again filled with ash, but the waste treatment plant remained operative (Schuster, 1981). 3 mm of ash in Ellensburg overloaded stormwater systems, but the network was kept operative by workers using high pressure water cleaners (Schuster, 1981).

6.2.2 Mt Spurr, Alaska, 1992

Another example of ash impacting wastewater systems is the 3 mm of volcanic ash deposited on Anchorage during the August 1992 eruption of Mt. Spurr volcano. Although steps were taken to minimize the amount of ash entering the stormwater system, large amounts of ash still had to be removed during the following spring, as pipe blockages caused some localised flooding. The ash had by that time formed a "hardened deposit" that was more difficult to remove (Johnston, 1997b).

6.2.3 Rabaul, Papua New Guinea, 1994

The 1994 Rabaul eruption from Tavurvur and Vulcan resulted in between 100 and 950 mm of ash being deposited in Rabaul itself (Blong, 2003). The town's sewage system was not extensive; it served about ¼ of the town, and consisted of two pump stations and an Imhoff tank treatment plant. Both of the two pump stations and the treatment plant were damaged by the amount of ash entering the system and were decommissioned (SMEC 1992, p7). The stormwater system was separate to the wastewater system, but suffered a similar consequence. It was quickly inundated by ash and subsequently buried under 2 metres of ash and mudflows. Five years after the eruption more than 65 % of the original road and drainage networks were still covered with volcanic debris (SMEC 1992, p7). The extent of the damage in Rabaul makes it difficult to extract meaningful information from this eruption about wastewater system capabilities and vulnerabilities to ashfall.

6.2.4 El Reventador, Ecuador, 2002

The 2002 eruption of El Reventador Volcano resulted in 4 mm of ash falling on Quito. Residents in Quito already had some experience with volcanic ash; the 1999 eruption of Guagua Pichincha also deposited ash on the city. A rapid cleanup by residents and the military (along with a very light rain that stabilised the ash) helped to prevent a lot of the ash from entering the stormwater drainage system. Ash that entered drains did not cause damage to equipment, but did increase the need for pump maintenance (Leonard et al., 2005). In a few barrios (street blocks), enough ash moved into storm water systems to cause localised flooding after the eruption (PAHO, 2003). Local calculations suggest that about 300,000 tonnes of ash was shovelled from drains in Quito after the eruption. The lack of wastewater treatment facilities in Quito meant there were no impacts in this regard (Alberto Palacios, EMAAP, pers comm., 2004).

At a distance of 45 km from Reventador, the region of Oyacachi suffered some damage to its sewage treatment plant. Pipes in the oxidation lagoon were obstructed by ash, causing the oxidation process to fail. This resulted in a strong smell being emitted from the lagoon, (PAHO, 2003, p37).

6.2.5 Etna, Italy, 2002

The 2002 eruption of Mt Etna, Sicily resulted in small amounts of ash being deposited on the city of Catania several times over a 3 month period (Barnard, 2004). Combined with occasional heavy rain the ash caused many blockages in the local stormwater system, causing localised flooding on several occasions (figure 6.1).

Figure 6.1: Ash in Catania during the 2002 Etna eruption. Clockwise from top left, sedimentation in open drain, blocked stormwater drain, localised flooding due to ash in drains.

6.3 Ash ingress to reticulation systems

Ingress of ash into sub-surface sewage networks is unlikely to occur in large quantities unless the network is connected to the stormwater collection system. Ash from roads, rooftops/drainpipes, driveways, pavements - in short any surface area, has the potential to be washed into stormwater drains. This is naturally more problematic during wet weather, however significant amounts of water are used in most ash clean ups, by officials as well as the general public. The hosing of ash into drains is a common occurrence. While actions may be taken to prevent ingress of ash into drains, these are usually not 100% successful, and will only serve to lessen impacts rather than prevent them.

There is no sure way to prevent at least some volcanic ash entering stormwater drains. Recommendations from the US Geological Survey website on keeping ash out of drains are based on lessons learned by F.E.M.A. after the 1980 Mt St Helens eruption. Those methodologies are summarized in figure 6.2. The amount entering systems will depend not only on the amount of ash falling, but on rainfall, clean up methodologies, the presence of any illegal waste connections and care taken to limit ingress into the system.

Suggested measures for reducing effects of ash to sewage and stormwater systems

- Have local ordinances in effect banning connections of downpipes and roof drains to the sewer.
- Instruct the public how to protect stormwater systems (protect manhole covers from ash, disconnect downpipes when possible, ash disposal instructions).
- Instruct citizens where to deposit ash cleared from property.
- Warn citizens against disposing ash down manhole access of both sewer and stormwater systems.
- When hosing streets, place sand bags around or over manhole covers or avoid them entirely, because holes in the cover and the areas between the cover and the rings allow passage of ash.
- When possible, disconnect downpipes from the stormwater system until ash is removed from the roofs of homes and buildings.
- Closely monitor the cleanup activities of privately-owned parking areas.
- Use dry methods, like hand sweeping, prior to flush cleaning with water when clearing streets and parking areas that are served by a free-discharging or dry-well stormwater systems.

Note: Shallow deposits of ash in the stormwater or sewerage system will not reduce the hydraulic capacity of the pipes by a significant amount; thus expenditure of time and money in these circumstances to clean lines may not be warranted.

Modified from, FEMA, 1984

Figure 6.2 Suggested measures for reducing effects of ash to sewage and stormwater systems (USGS, 2009)

Determining the potential amount of ash that may enter a shared stormwater and wastewater system is extremely difficult given the many parameters needed to create an equation to do so. Excluding whether ash is washed into drains during hosing in cleanup situations, or prevented from entering drains by sand bagging in other instances, the following variables have an influence on the amount of ash that will enter the wastewater system.

- The amount (volume) of ash in the catchment area. The thickness is measurable but spatially variable.
- The amount of rainfall during ashfall and while ash is on the ground. This may be predicted using meteorological records.

- The amount of rainfall from the catchment entering the system. Some will be lost to evaporation, some will fall on permeable areas and soak into the ground. Determining this for a given rainfall event is dependant on city records of flow through the system – these data may not be measured. This would also be affected by drains becoming blocked and any subsequent surface flooding.
- The amount of ash entrained by water. This parameter is in turn dependant on the:
    - Grainsize of the ash (measurable).
    - Flow velocities of water on the ground. This is extremely variable in hilly areas. The formation of channels in ash deposits will also affect this.
    - Degree of cementation of ash – not applicable immediately after ashfall, but subsequently after ash has been wet then dried out, or wet for over a few hours.

For these reasons any estimate of the volume of ash entering a system is going to be extremely vague. However to illustrate the order of magnitude of the amount of ash available to be washed into a system, a simple calculation of the surface area of the shared network multiplied by an ashfall thickness can be made. Assume a 100km^2 area (which equates roughly to the area served by the shared network in central Auckland).

For a 1 mm thickness of ash: 100 km^2 x 1 mm ash = 100,000 m^3

Even if only 1% of this entered the shared system, this is still 1000 m^3 of ash to deal with, in addition to the usual volumes of solids. Taking Auckland as an example, under normal circumstances 108,000 tonnes of biosolids are removed by the Mangere treatment plant annually. This averages out at 296 tonnes per day. 1000 m^3 of ash would equate to between 1000 and 1600 tonnes of solid material, a significant addition to the usual amount of solids entering the system. With a higher amount of ashfall, for example 5 mm, and more ash (perhaps 2%) entering the system, the shared wastewater and stormwater system could have 10,000 m^3 of ash (10000 – 16000 tonnes) to cope with. These figures are quite arbitrary, but reflect the degree of uncertainty about how much ash may enter a system.

Given the vast quantities of ash that even a 1 mm covering on a large urban area represents, almost any amount of ashfall has the potential to cause widespread disruption and/or damage to wastewater reticulation networks and sewerage treatment facilities. While the instances of ashfall impacting wastewater systems described in section 6.2 give an indication of potential impacts, only the Yakima example gives a detailed example of what may happen if ash is carried through a reticulation network to a treatment plant. This example however, provides insufficient information to derive quantitative data on network vulnerabilities. Some types of impact can be satisfactorily predicted with a knowledge of the properties of volcanic ash and an understanding of wastewater systems. For example the low pH often associated with ash leachates can easily result in lower pH levels of sewage as ash and ash leachates enter waste systems. As pH levels in reactor-clarifiers are carefully balanced to allow bacteria to break down organic nutrients, it is clear a large influx of acidic sewage will cause major problems for this process. However there are also impacts which cannot be accurately predicted. Of most importance is the impact of vast quantities of volcanic ash passing through effluent pumps. Pumps are essential to the operation of any sewerage network and/or treatment facility. Even if treatment plants are bypassed to protect plant equipment, pumps are still necessary to move waste through networks. Without them working, sewage may back up and spill into built up areas, causing significant health hazards. Backups may be alleviated by overflow channels, depending on the system and the degree of blockages.

6.4 Volcanic ash and pumps

In some cases it has been observed that pumps have become blocked during large influxes of ash into the waste water system (e.g. at Yakima during the 1980 Mt St Helens eruption). This is due to the large volumes of solid matter (ash) passing through the pumps. What is unknown is the amount of ash required to cause such blockages and the long term effects on pumps should they keep operating. Pump type and rating, required hydraulic head and the sump geometry will all have an effect on whether blockages occur, as will the grainsize of the ash. The quantity of ash and the amount of water present is the biggest factor in determining whether failure will occur. Most wastewater pumps are designed to be able to cope with up to 4-6% solids material in waste sludge, some are rated slightly higher (up to 8%) and some lower (down to 2%) (B. Park, pers. comm., 2006). Even without blockages occurring, abrasion of pump components (e.g. impellers) will increase, as ash is both abrasive and often corrosive.

Testing municipal wastewater pumps to determine how likely they are to become blocked with volcanic ash, and how quickly pump components are abraded is not feasible. This is dictated by the size of urban wastewater pumps, with some of the pumps used being capable of pumping waste volumes of up to 1.125 m^3 per second. This would require immense quantities of volcanic ash, and a pump set up with a large sump that allowed for recirculation of material. With a cost of NZ $25000 just to overhaul such pumps, testing on this scale would be an expensive undertaking. Variations between pump types (and ash types) would also mean that several tests would need to be carried out for precise results.

The lack of published data on effects of volcanic ash in wastewater reticulation networks requires an experimental approach to determining possible impacts of ash travelling through the system. Because of this a series of pump tests were undertaken on two smaller pumps, to give an indication of the potential impacts of volcanic ash on urban wastewater pumps, and determine potential failure mechanisms.

6.5 Laboratory work

Two pump types were tested to determine how well they would cope with pumping volcanic ash. The lack of availability of fresh, fine-grained volcanic ash necessitated the use of crushed volcanic rock. Crushed Port Hills basalt was again selected as a proxy for ash, as described in section 3.5.2.1. For these tests samples were passed through a 710 µm sieve to remove large particles. As sizeable volumes of ash were needed, sediment taken from Mt Ruapehu’s Whangaehu lahar in March 2007 was also used in some tests. This andesitic sediment was collected from the later stages of the lahar, approximately 25km downstream from source. Lahar material was put through a Micromeretics Saturn Digisizer 5200. The grainsize ranged from 0.88 µm to 434.01 µm, with a modal grainsize of 188.7 µm and a mean of 106.5 µm. The samples were quite acidic, resulting in a low pH in the ash mix used in effluent pump testing.

6.5.1 Finsbury vortex pump testing

Preliminary pump testing was undertaken using a Vortex Pool 5000 pump, manufactured by Finsbury Pumps, South Australia. This type of pump is designed to pump water rather than effluent, and is usually used as a swimming pool pump. While significantly different to wastewater pumps in size and materials used for construction (e.g. a plastic rather than cast iron or steel impeller), the principals on which it is constructed are similar. However pump type was not critical for these tests, as the tests conducted using this pump were not intended to establish potential impacts on wastewater pumps. They were performed to:

a) Determine potential areas of sedimentation in pump station sumps.
b) To establish a methodology that would allow for accurate testing when an effluent pump was tested.

Testing was conducted by pumping ash-leaden water through the pump, into a sump and then circulating back into the pump. The sump was designed with a hemispherical cross section, with the pump intake end narrower than the opposite end. Between the wider and narrower ends was a lip as the wide part of the sump narrowed (figure 6.3). This mirrored the shape of the sump in pump station 16 (PS16) Orakei, Auckland.

Figure 6.3: preliminary testing using a pool pump and hemispherical sump narrowing at the intake end

Water was pumped through the system to begin the test procedure, and ash was gradually added in 1% by volume (total fluid) increments, with any changes noted. The first test run used a coarse unsieved mix of crushed basalt. Much ash immediately settled out of suspension, despite the highly turbulent water. As expected the turbidity of the water immediately increased dramatically, the pump began to work harder. As more ash was added the turbulence of the water decreased and the turbidity increased. By the time 5% of ash had been added to the water the pump was still performing, but much ash had settled on the floor of the sump. Sedimentation was especially prevalent where the sump narrowed

The second round of testing used a finer ash, the same crushed basalt as used previously, but passed through a 710 µm sieve. Results were largely unchanged from the previous test, the exception being that more ash remained in suspension. Testing again stopped after the amount of ash in the system reached 5% by volume.

A third test run used crushed basalt with a grainsize < 105 µm. The increased amount of ash held in suspension meant the pump had to work harder than previously. Once ash volumes reached 4% of the total fluid the pump quickly overloaded the 10 amp power supply, triggering a safety cut-out.

Subsequent to testing, the pump was inspected for signs of wear, but none were detected. No detrimental effects appeared to have taken place, aside from the increased load. Total run time of each test was approximately 15 minutes, from start to finish, including initial operation with clean water. More obvious wear may have been apparent after a longer test period.

While these tests did not indicate possible impacts of ash on effluent pumps they did indicate that sedimentation is likely to occur in pump station sumps as coarse ash accumulates. The tests also indicated load would increase on pumps as the sediment load increased.

6.5.2 Effluent pump testing

Effluent pump testing was conducted on a *Zenit Draga* submersible waste pump, with a vortex set-back impeller (figure 6.4). These pumps are normally used in a variety of functions. According to the manufacturer these pumps are suitable for: “civil or industrial water treatment plants, for use in hospitals, agriculture, sanitary facilities, mining, irrigation, marble and stone work, lifting and transfer in industrial and civil installations, treatment of low and medium density industrial sludges, and for installation in public facilities, hotels, sports facilities, and campgrounds” (Zenit, 2009). The model used was a *DGE 50/2/G50V AOBM-E.* This pump is used in New Zealand for similar applications to those listed above, especially as an agricultural effluent pump. The pump is fully submersible, with a maximum head of 6 metres. The casing and impeller are constructed from EN-GJL-250 cast iron. The recessed impeller allows for the free passage of solid bodies up to 35 mm.

Recommended pH levels for the pump to operate in are 6 to 10. While this may be practical under usual operating conditions, lower pH levels can be expected in wastewater systems after the deposition of volcanic ash. The pH levels of the ash-water mix used in testing were significantly lower than those recommended, ranging between a pH of 2.8 and 5.3.

Figure 6.4: Zenit DGE 50/2/G50V effluent pump pre-testing. With base removed (left) and fully assembled (right).

6.5.2.1 Methodology

Prior to testing, the pump was carefully photographed and the impeller was measured and weighed. This enabled a comparison of the pump pre and post-testing. In this way the amount of wear sustained could be established. Other parameters monitored included the output of the pump (litres per second), the pH of the fluid being pumped and the concentration and grainsize of the ash. The current drawn by the pump was also monitored, but this did not fluctuate beyond normal levels during the course of the experiment. As the objective of this test was to determine the effects of effluent pumps being subjected to volcanic ash, the shape of the sump was not important. The sump simply needed to contain the ash-water mix and allow it to be recirculated. An old bath was used, and the effluent pump placed at one end. A pipe leading from the outlet directed the water back to the other end of the bath (figure 6.5). As the pump displaced approximately 9 litres of fluid per second, most of the ash remained in suspension, and only minor amounts of sedimentation occurred.

Figure 6.5: Effluent pump test set up shown during initial clean water test

Several different tests were performed. During initial tests ash was gradually added to the water being pumped to ascertain if there was a threshold at which blockages would occur. Later tests ran the pump for longer at a higher concentration of ash to determine further impacts and test for abrasion and corrosion. Finally a long duration test was conducted to establish long term impacts.

6.5.2.2 Testing

Two tests were conducted during which the ash-water ratio was gradually increased. These tests differed in that a fine ash was used in one test and a coarse ash in the other. The first test used crushed Port Hills basalt, sieved through a 105 µm sieve. Concentrated sulphuric acid was added to the mix to more closely simulate an ash leachate. Results are given in table 6.1

Time (min)	% Ash concentration	Flow (L/s)	Acidity (pH)	observations
0	2	9.1	4.5	-
10	3	9.0	3.8	-
20	5	8.9	3.7	-
30	7	8.9	3.7	-
40	9	9.0	3.4	-
50	11	9.1	3.3	-
60	13	9.0	3.1	-
70	15	9.0	3.1	-
80	21	9.1	3.1	-

Table 6.1: Results of fine ash (<105 µm incremental test, Zenit DGE effluent pump

As illustrated by table 6.1 initial results indicated no drop off in performance. The pump continued to operate well, and pump at the same rate as it had prior to testing. Variations in the output are more likely due to small errors in measurement than actual changes in flow rate. Figure 6.6 illustrates the experiment in progress.

Figure 6.6: Circulating ash laden water through the Zenit effluent pump.

The second test used a coarser ash, made up of crushed Port Hills basalt and lahar sediment from Mt Ruapehu. The measured grainsize of this mix ranged from .9 µm to 613.06 µm with a mode of 211.7 µm and a mean of 140.4 µm. Similar results to the first test were experienced, depicted in table 6.2. Again performance was not affected by the increase of ash, no blockages occurred and the flow rate remained the same.

Time (min)	% Ash Concentration	Flow (L/s)	Acidity (pH)	observations
0	2	9.0	3.5	-
10	3	9.0	3.5	-
20	5	9.2	3.4	-
30	7	8.9	3.1	-
40	10	9.1	3.1	-
50	12	9.0	3.0	-
60	15	9.0	3.1	-
70	18	9.0	3.1	-
80	22	8.9	3.1	-

Table 6.2: Results of coarse ash incremental test, Zenit DGE effluent pump

The lack of blockages or other apparent impacts indicated that for this type of pump any impacts were likely to take place over a longer period of time. During the tests already conducted, once a high percentage of ash was reached the pump was only run for a few minutes. For that reason further tests were conducted, with a constant high percentage of ash passing through the pump, to determine whether this would cause any impacts. The first such test used the same ash as the previously used (mean grainsize was 140.4 μm, maximum grainsize of 613.06 μm). This ash made up 15% of the total fluid volume being pumped. Once again the pump continued to operate as per normal (table 6.3).

Time (min)	Ash Concentration	Acidity (pH)	observations
0	15%	3.3	-
10		3.3	-
20		3.3	-
30		3.3	-
40		3.3	-
50		3.3	-
60		3.3	-
70		3.4	-
80		3.3	-

Table 6.3: Results of coarse ash 80 minute test, Zenit DGE effluent pump

A second test used the same ash, but passed through a 105 μm sieve, and at a higher concentration of 21% by volume. This provided similar results to the coarser ash test.

Time (min)	Ash Concentration	Acidity (pH)	observations
0	21%	4.6	-
10		4.6	-
20		4.5	-
30		4.6	-
40		4.6	-
50		4.5	-
60		4.6	-
70		4.5	-
80		4.5	-

Table 6.4 Results of fine ash (<105 μm) 80 minute test, Zenit DGE effluent pump

The effluent pump functioned well in the short term, but needed to be tested for a longer period. A 24 hour test was conducted to ascertain whether any impacts would occur over a longer timeframe (table 6.5).

Time (hours)	Ash Concentration	Flow (L/s)	Acidity (pH)	observations
0	21%	9.1	2.8	-
2		9.0	3.0	-
4		8.9	3.1	-
6		8.9	3.3	-
8		9.0	3.3	-
12		9.1	3.3	Increased noise from pump
16		9.0	3.3	-
20		8.9	3.3	-
24		8.9	3.2	-

Table 6.5: Results of fine ash (<105 µm) 24 hour test, Zenit DGE effluent pump

At the end of this test the pump was removed and inspected, to determine if any detrimental effects had taken place. It was found that significant corrosion and abrasion had occurred, as illustrated in figures 6.7 & 6.8

Figure 6.7: Pump impeller pre testing and after ~29 hours of testing. Impeller blade measurements illustrate the extent of abrasion; A-A^{l} was 65 mm pre testing and 62 mm post test.

The impeller had been abraded both on its base and blades. Its diameter had decreased slightly, from an initial 101 mm to 99.3 mm. The impeller blades had also decreased in width, the tips of the blades were especially worn (figure 6.8). The distance between each end of the base of each blade was 65 mm pre testing, as illustrated in figure 6.7. A-A^1 was 62 mm after these tests, the other blades measured 62.8 mm and 63 mm. All paint was worn away from both the impeller and the inside of the housing. Pitting was evident on impeller blade surfaces, though it cannot be ruled out that this was not present before testing, as in new condition paint obscured the surface.

Figure 6.8 Impeller after ~29 hours testing, note wear on the tips of the blades.

This level of wear was judged to be consistent with what would normally be seen after 1-2 years of pumping cowshed effluent (H Baker, pers. comm., 2008). Total run time from new had been just over 29 hours. Therefore while the pump had kept functioning it had been subject to extremely accelerated wear.

6.5.2.3 Long term testing

Determining impacts and wear over a longer period required more testing. As such the pump was run again for a longer duration test. Ash used was again the mix of crushed Port Hills basalt and andesitic material derived from the March 2007 Whangaehu lahar (grainsize 0.9 µm to 613.06 µm with a mode of 211.7 µm and a mean of 140.4 µm). The pH was 5 at the beginning of this test, but increased slightly during the test process due to buffering by the ash. This was countered by the addition of small amounts of sulphuric acid as required, keeping the pH at 5 ±0.3. This test was conducted with a smaller volume of fluids (45 litres), using a large barrel to circulate the ash and water within. Five litres of ash were added to the 45 litres of water. The pump was left running on a timer, which periodically switched off to allow the pump to cool down. This would not usually be necessary, but the small volume of the barrel meant that the water warmed up due to the heat generated by the pump, and the pump would have run the risk of overheating had it been left to run constantly.

For this first part of the longer duration test the pump ran for 56 hours. Inspection at the conclusion of this test revealed severe abrasion to the impeller, and increased levels of corrosion. The impeller blades were again shortened. The initial 65 mm length for each of the 3 blades described in figure 6.7 now measured 55.8 mm, 56.3 mm and 55.1 mm respectively. The serial number of the impeller, which was stamped into the cast iron surface, had also been worn away, indicating the base of the impeller was also subject to erosion (figure 6.9).

Figure 6.9: Impeller after 85 hours testing, note the stamped serial number is now not visible.

Pitting on the impeller blades had also increased (figure 6.10). It was now obvious that the mass of the impeller had decreased, as it was noticeably lighter. It was weighed and found to be 310.6 grams. Initial weight before testing was 448 grams. This loss of over 30% of it's mass represents severe wear for such a short length of time (total test time was now 85 hours).

Figure 6.10: Pitting on the surface of the impeller blades

Figure 6.11: Impeller casing interior, showing minor abrasion (smoothed internal edges) and increased corrosion.

Minor wear was also evident on the interior of the impeller casing, as was increased corrosion. Surface rust was visible on both the impeller and the interior of the pump housing (figures 6.10 & 6.11). Corrosion and wear were especially noticeable behind the impeller, and on the back of the impeller itself. Ash was visible around the shaft of the impeller, behind the sleeve around the spring holding the seal ring. This meant that ash would be in contact with the seal which separated the motor and electrics from the wet impeller area, potentially abrading both shaft and seal (figure 6.12).

Figure 6.12: Arrow indicates ash visible behind the sleeve rubbing against the shaft and seal. Impeller removed for inspection and photograph

After inspection and reassembly, testing continued. The pump was run for a further 24 hours. As expected, increased wear was again seen. Most significantly, the impeller base had begun to wear through at the thinnest points. These had started as small indentations on the back of the impeller but had increased in size through abrasion during testing (figures 6.13-6.14).

Figure 6.13: Heavily eroded impeller after 109 hours of testing

Figure 6.14: Rear views of the impeller showing the increase in erosion in the rear indentation. Images were taken (from left to right): pre testing, after 29 hours, after 109 hours.

The loss of much of the impeller represented a significant decrease in the efficiency of the pump. The length of the 3 blades described in figure 6.7 now measured 52.0 mm, 53.2 mm and 52.9 mm respectively, approximately 80% of their original length. Flow rate was again measured, and found to be 7.5 L/s, the original flow rate was ~9 L/s. Testing resumed in order to determine how long it would take until complete pump failure occurred. This happened only 3 hours later, not because of impeller wear but from failure of the seal separating the electric motor from the impeller and wet area. The seal itself was made from silicon carbide (9 on Mohs scale of hardness), this survived without any signs of wear. The stainless steel impeller shaft however had suffered pitting corrosion, especially between the seal and the shaft. This allowed ash to work its way past the seal. It then became trapped under the seal ring (situated above the mechanical seal), wearing a groove into the metal shaft (figure 6.15). After 112 hours of testing, ash and water broke through into the electric motor, causing the pump to fail (figure 6.16). This failure created an electrical short that blew a fuse in the wall socket.

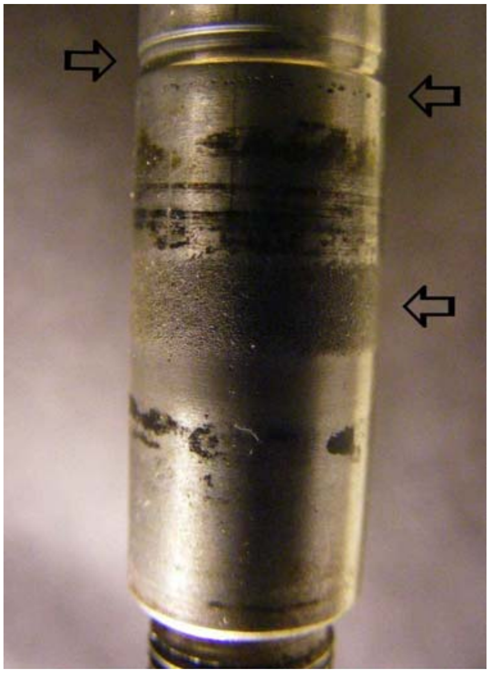

Figure 6.15: Impeller shaft after 109 hours of testing. The lower arrow indicates the rough pitted surface caused by corrosion between the seal and shaft, the middle arrow indicates further pitting, the groove (left arrow) is caused by mechanical abrasion beneath the seal ring.

Figure 6.16: Pump at end of testing. The puddle is all from the interior of the pump, which should be dry.

The failure effectively destroyed the pump. The pump had a design life of 20 years, and was designed to handle noxious substances like effluent, but was not robust enough to cope with volcanic ash. Even without the failure of the seal, the severe abrasion to the impeller would have made the pump inoperative within a few more hours of testing. By the end of testing the impeller weighed 273.8 grams; 39% of its original mass had been removed by abrasion.

6.5.3 Implications of testing – applying results

The 112 hours that the Zenit effluent pump survived for illustrate some of the problems associated with pumping volcanic ash. Test results cannot simply be scaled up to approximate a larger urban effluent pump, in any case there is no standard type pump used in wastewater systems. However the tests clearly demonstrate that pumping volcanic ash will result in vastly increased wear, compared to wear achieved under normal circumstances. Urban waste water pumps use similar materials for construction to the effluent pump tested, so wear is likely to occur in a similar manner. Rapid destruction of the impeller is therefore a likely outcome for any wastewater pump.

The failure of the seal as an issue will not translate to all larger pumps, as in many cases urban wastewater pump motors are mounted significantly higher than the impeller, connected by a long drive shaft. These pumps are not submersed like the effluent pump tested. In these instances the failure of a seal would result in some spillage of sewage, but no other damage.

The lack of blockages in these tests does not imply that blockages will not occur in metropolitan wastewater pumps, as previous instances of ash causing blockages to such pumps have been recorded. Whether or not pumps become blocked, ash will be extremely problematic; where blockages do not occur, damage to pumps, (particularly impellers) will.

6.6 Other wastewater system vulnerabilities to volcanic ash

There are several different ways in which volcanic ash may impact wastewater/sewerage systems. This is because in addition to ash entering the wastewater system through stormwater drains etc, direct ashfall may cause problems for associated surface infrastructure. This includes pumping stations and the equipment within, power supplies, communications equipment and most significantly the treatment plant itself. To accurately determine potential impacts of ashfall on a wastewater system, a specific system (Auckland) was selected to have a vulnerability analysis conducted on it. Auckland was chosen as an example of a New Zealand city with a typical urban wastewater reticulation network, and because it is a city at risk from volcanic ashfall from several different volcanic centres (Houghton et al., 2006). Furthermore it is New Zealand's largest city (population 1,303,068), home to over 32% of New Zealand's population (Statistics NZ, 2009). This fact, combined with the associated industry, infrastructure and presence of the busiest airport in New Zealand, make it the most economically significant centre in New Zealand.

6.7 The vulnerability of Auckland city wastewater collection system and treatment plant to volcanic ash.

Potential impacts of an ashfall in Auckland on stormwater and sewage systems can be broadly divided into two sections – impacts on the network and impacts on the wastewater treatment plant. Both the network and the treatment plant will be vulnerable in some ways to both airfall ash and ash transported through the pipes of the wastewater system.

6.7.1 Network impacts

While most suburban areas around Auckland have separate stormwater and sewerage networks, Auckland City itself has a shared sewerage/stormwater network, the 'Orakei Main Sewer' and it's branches (figure 6.17). This means that should an ashfall impact Auckland, volcanic ash will enter the sewerage system in the Auckland CBD and surrounds, mainly via stormwater drains. The area served by the Orakei main sewer creates ~30% of the entire intake of effluent at Mangere treatment plant.

The Orakei Main Sewer feeds into the Eastern Interceptor. It is these lines and their pump stations that will be subject to ash entering the network. The amount of ash entering the network will depend on not only the amount of ashfall, but also the amount of rainfall. Approximately 71% of the Auckland isthmus is covered by impermeable surfaces (Auckland City Council 2007b). Because of this, most rainfall will end up draining into the stormwater system as opposed to soaking into the ground.

Figure 6.17: (Overleaf) Auckland Waste water Reticulation Network. The central Auckland area served by the Orakei main sewer (orange) uses a shared stormwater and sewerage system. Mangere treatment plant is located with an asterisk. Map © Watercare 2005

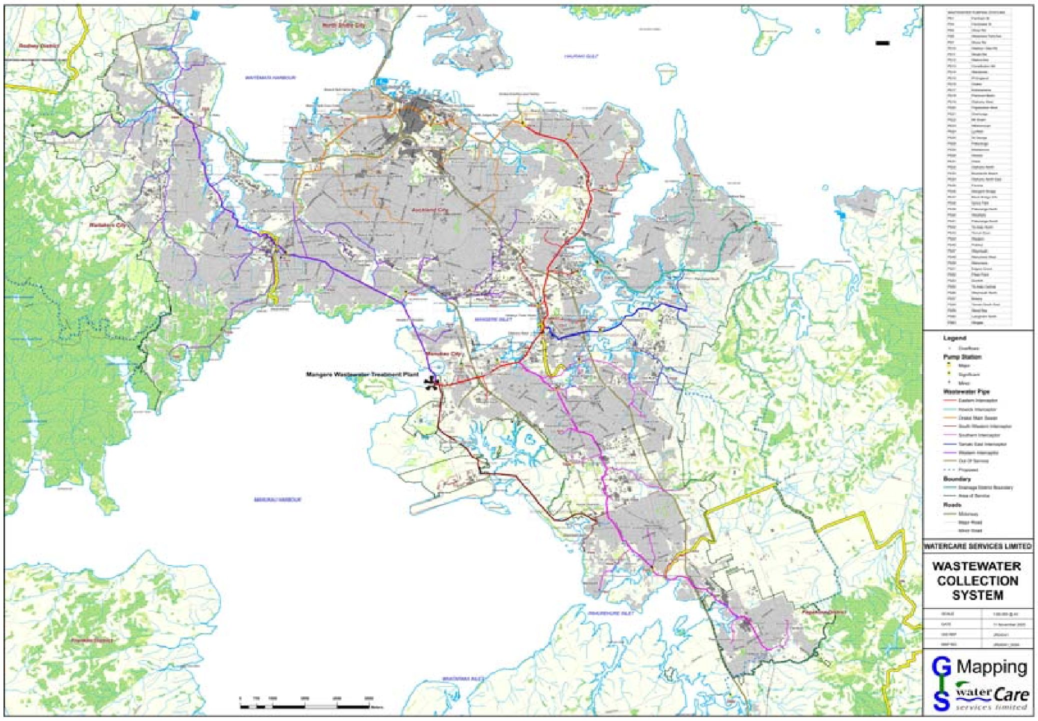

Figure 6.17: Auckland Waste water Reticulation Network. The central Auckland area served by the Orakei main sewer (orange) uses a shared stormwater and sewerage system. Mangere treatment plant is located with an asterisk. Map © Watercare 2005

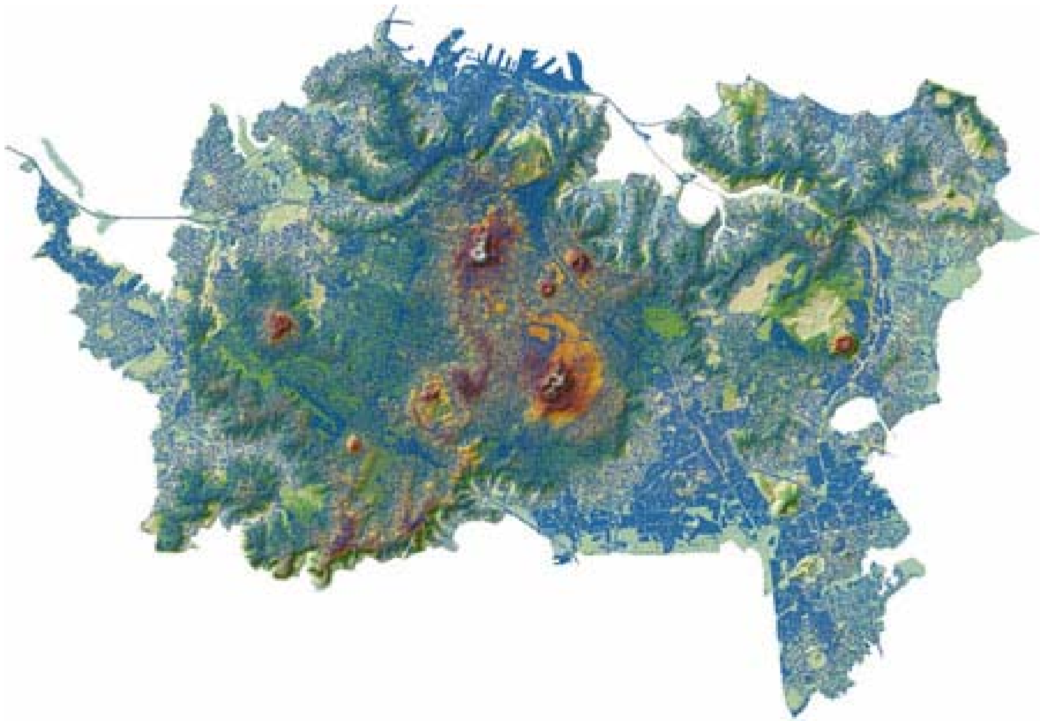

Figure 6.18: Impermeable surfaces (coloured blue) in Auckland in 2002 (Auckland City Council, 2007a)

Stormwater and sewage reticulation systems constructed in New Zealand after the 1940's are generally designed to be self cleansing under most flow conditions (Kamer, 1993). The gradient and shape of pipes (narrow at the base) encourage high flow velocities, even during dry weather when low amounts of waste are flowing through the system (B. Park, pers. comm., 2006). This helps to entrain sediments and move them through the system. However accumulations of sediment still occur, even without extreme conditions like ashfall taking place. For this reason most systems have grit chambers (sediment traps) in place to capture coarse or heavy sediment (e.g. grit from roads) rather than transport it through the system. These are typically in the order of a few cubic metres capacity. Those in Auckland City range between 1.7 m^3 and 21.1 m^3, apart from a large sediment trap at Ngapipi Road, which has a total volume of 94 m^3 (Kamer, 1993). While under normal circumstances grit chambers are cleaned out 2-3 times per year, even a light ashfall will result in rapid accumulation of material in the chambers, necessitating markedly increased maintenance and cleaning.

A lot of ash will bypass the chambers completely, being carried in suspension through the system. As fine components more readily remain in suspension, the grit chambers will be more effective in capturing coarser ash – thus a local eruption from the Auckland Volcanic Field (AVF) will rapidly deposit ash in the grit chambers, even in a small-scale eruption. The time it will take for the traps to reach capacity is very difficult to predict, for the same reasons that the amount of ash entering the system is unconstrained - the large number of variables include ash grainsize, quantity, and fallout rate. It also depends on the amount of rainfall during or after ashfall, preventative measures taken to stop ash entering the system, flow velocities at the grit chamber, and the size and morphology of each chamber. Emptying grit chambers during ashfall may be problematic due to access issues; roads may be closed, and hills difficult to climb due to traction problems. Vehicle mobility on ash covered roads is discussed in chapter 5.

During slow or waning flow conditions, ash carried in suspension will begin to settle and accumulate. As it dries a limited amount of cementation and hardening may begin. In this way blockages can begin to occur. This was observed in the sewerage system in Anchorage following the 1992 Mt Spurr eruption (Johnston, 1997b). While some of these blockages can be removed with high pressure water, others may require mechanical shifting. Other examples of ash deposits hardening after drying (outside of wastewater environments) have been observed on several occasions, e.g. Etna 2002 (Barnard, 2004). Figure 6.19 shows residents cleaning up ash after the May 20 2006 dome collapse of Soufriere Hills volcano on Montserrat. The hardness of the ash is illustrated by the tools used to clean it; hoes rather than brooms.

Figure 6.19 Clean up of ash using hoes, Montserrat, 2006 (image from Montserrat-today.com, 2006)

6.7.2 Mitigating impacts of ash entering the network

- Preventing as much ash as possible entering the system will reduce further impacts. Recommended steps to do this are listed in figure 6.2.
- In the event of large amounts of ash entering the Orakei main sewer the overflow at PS16 (64) may be used to spill sewage into Waitemata Harbour, preventing blockages occurring downstream in the network. In this instance a dredge will need to be available prior to overflow to keep the outlet clear.
- Grit traps will quickly fill. Additional staff and equipment to empty these as required need to be readied. It should be noted that access to these grit traps may be compromised by ash covering the ground and closing roads. Steep inclines need to be avoided by maintenance vehicles.
- Pump station wet wells will quickly become subject to sedimentation (exact impacts cannot be predicted as it is unclear how much ash pumps will be able

to keep moving). Maintenance staff need to be available to clear blockages if possible. This is more of an issue in light ashfall or for small pump stations on the Orakei main sewer, as it is likely during heavier ashfall that PS 16 (64) will be shutdown.

- Cleaning wastewater pipes will be necessary after (and possibly during) an ashfall. Sufficient equipment and staff need to be available to achieve this quickly.

6.7.3 Network vulnerability to direct ashfall

Excluding the treatment plant, wastewater infrastructure on the surface is limited. Some pipes are occasionally located above ground; such as the pipeline crossing the Orakei Basin. (This pipe is soon to be replaced with the newly constructed Hobson Bay Tunnel). As surface pipes are sealed they are unlikely to be affected by ashfall, aside from minor corrosion on any metal surfaces. Grit traps are covered by steel plates, so are unlikely to be greatly affected by ashfall aside from surface corrosion. This leaves pump stations, which are housed in purpose built structures. The pump stations and associated infrastructure do have some vulnerabilities to direct ashfall, which may affect them in several ways. Pump Station 16 (PS16) at Orakei is one of Auckland's major wastewater pumping stations; all of central Auckland's sewage and stormwater passes through this facility (figure 6.20). Upstream of this pump station the network is a combined system of sewerage and stormwater. Below it the sewerage and stormwater pipes are separate. Almost all ash to pass through the network will therefore pass through this pump station. Given it's importance, this station has been used to determine potential impacts of volcanic ashfall directly landing on pump stations. It will be retired soon, as a replacement station (PS64) is currently under construction, scheduled for completion in December 2009. However PS16 still represents a good example of a major pumping station, and will be in service until that time.

6.7.3.1 Pump stations

Tephra loading

These largely flat roofed structures will accumulate ash during ashfall. The danger of roof collapse will only be an issue during heavy ashfall. This is most likely in the event of a local eruption from the Auckland Volcanic Field. Probabilities of roof collapse on different types of structures are examined in section 2.3.1.4. The flat roof of PS16 is supported by steel joists, and would fit into the MW (medium-weak) category used in the proposed classification of European roof types for tephra fall resistance (Spence et al., 2005). This means a 3 kPa load will result in a 50% chance of collapse. This load represents approximately 20 cm of dry ash or 15 cm of wet ash, depending on tephra density. These figures assume a (worst case scenario) dry density of 1500 kg/m^3 and a wet density of 2000 kg/m^3 respectively. Roof collapse effects will vary depending on what objects are struck, but are potentially catastrophic.

Figure 6.20: Interior of pump room, Pump Station 16, Orakei.

Even without roof collapse, buckling of roofing iron under load may result in the ingress of ash and/or rainwater to pump stations. The effects of this will depend on where the ingress occurs and whether the ash is wet or dry. In the pump rooms, small amounts of ash and water will create a mess, but that may be the extent of any damage, as the pumps are located in a wet or at least damp area anyway. Wet ash will not remain airborne, and should not therefore cause issues for pump motors. Should an ingress of dry ash occur, some ash may accumulate on compressors and pump motor air filters. Assuming only minor amounts enter the pump station this is unlikely to be problematic.

Pump station control rooms will be more susceptible to damage if buckled roofs allow for the ingress of ash or water. Control room electronics will likely be damaged or destroyed if water (potentially including acidic ash leachates and ash particles) is directed onto them. Ingress of dry ash into this area is also likely to be damaging for electrical components, due to its conductive nature.

Even during light ashfalls of only a few millimetres ashfall can be damaging. The corrosive nature of ash will result in accelerated corrosion of roofing iron. Gutterings will be susceptible to collapse as rainfall washes heavy ash into them.

These impacts can be mitigated by cleaning ash off roofs where possible. Safety needs must be considered, as ash is not only slippery, but already overloaded roofs may be further damaged or collapse under the additional load of workers.

Ash ingress

During ashfall the ingress of ash into pump stations will be possible through windows, doors and other ventilation openings, even if the roof remains structurally sound. Vents allowing air into PS16 have either coarse or no filtration and there are gaps around doors (figure 6.21).

Figure 6.21: External and internal vents with either coarse or no filtration at PS16

The entry of ash into this facility has the potential to cause problems for the electronic control equipment for the pumps, and to the pump motors themselves. The control equipment, including the programmable logic controller (PLC) and switchgear, while situated in a separate room from the pumps, also uses vents with either coarse or no filtration. Small amounts of ash may penetrate these openings, especially in windy conditions. The conductive properties of fresh ash (especially when damp) give it the potential to cause arcing and thus short-circuiting of electrical equipment. Frequent inspection will be required to closely monitor any accumulation of ash in such areas, unless filtration of vents is improved, and seals are installed around doors and windows. This is likely to occur with the current construction of pump station 64, replacing PS16.

Figure 6.22: PS16 control room and switchgear

The air-cooled electric pump motors situated in the main room of the pump station also face a hazard posed by the presence of volcanic ash, as do the drive-shafts connecting pumps to motors. The abrasive nature of volcanic ash is the main concern, since any moving parts on the machinery will be subject to increased wear as ash penetrates the equipment. The presence of a small amount of ash inside this room is not likely to cause failure of this equipment.

Compressors used to inject bubbles of air into wet-wells should not be used while ash is entrained in the air, as an influx of ash into a compressor will cause damage to seals, dramatically reducing the effectiveness of the compressor. Air filters on the compressors will also be subject to blockages.

Whilst filters will quickly block if air is being drawn through them, in the absence of constant airflow (there is no fan drawing air inside) filtration should adequately provide protection without blocking in the short term. Fine filter (EU6-7) media will keep much of the ash out, though should be used in conjunction with a coarser pre-filter (e.g. EU2-3) to increase the time taken for blockages to occur.

Communications

Monitoring of the pump station status in Auckland takes place remotely, from a control room situated in Newmarket. This is achieved via radio telemetry from the pump stations. Communications with the pump stations have the potential to be disrupted in a local eruption, as electrically-charged ash in an eruption column can cause interference and render radio systems inoperative. This is by no means certain to happen, as there are other instances of radio communications continuing to function near eruptions and in areas receiving ash falls (refer to chapter 2). The location of the telemetry equipment outside of the pump station building is potentially problematic, as the system has several vents, which could allow the equipment to be coated with conductive volcanic ash. This may cause flashover and possible failure of the transmitter, but the equipment has not been tested with ash, the vulnerability of the unit is therefore unknown.

Another part of pump stations (and siphons) are the biofilters. They consist of large open air beds (up to 90m^2) of bark, scoria and organic material, hosting bacteria that help to reduce odours. While thin (< 2 millimetre) deposits of ash may not significantly impact these structures, thicker deposits have the potential to result in pH changes that could affect the bacteria within these filters. Effects are largely unknown, however the creation of unpleasant odours is unlikely to be a high priority during ashfall. Rapid cleanup will mitigate this occurrence.

Power failure

A significant immediate impact on wastewater pumping stations during ashfall may be power cuts. These are a common occurrence during ashfall, due not just to flashovers in substations, but also to the collapse of power lines from both direct ash loading and trees/branches falling under the weight of volcanic ash (Wison et al., 2009). Traffic accidents and collisions with power poles due to the slippery conditions caused by light ashfall may also result in some power failures. Temporary shutdowns of pumps stations will result in sewage backing up in pipes. While some storage capacity is created by the volume of the pipes themselves, ultimately this will result in overflows. An example of this was seen on June 12 2006, where a power cut of a few hours resulted in PS16 (among others) shutting down. An overflow channel at Orakei would normally discharge into the sea, but in high tide conditions this failed, resulting in the flooding of Kelly Tarlton's Antarctic Encounter and Underwater World with raw sewage (Beston, NZ Herald, 14/06/06). A more recent example occurred on February 3rd 2009, when power cuts for only 2 and a half hours resulted in the discharge of sewage into Waitemata harbour at St Heliers and Orakei (due to the shutdown of PS16) (NZ Herald, 04/02/2009). A greater temporary storage capacity will be available by December 2009 when the new Hobson Bay Tunnel (sewerage pipeline) is brought into service, increasing the buffering capacity as pump stations are put under pressure.

Once pumps have failed, due to blockage, damage or power failure, waste will begin to fill the Hobson Bay Tunnel section of the Orakei main sewer. This section of the sewer will act as temporary storage for waste when PS16 (64) pumps cannot keep up with wastewater supply. Under normal conditions this would occur when flows exceeded 7500 l/s (B Park, pers comm., 2009). The ponding of waste will result in the deposition of suspended ash as it settles out of suspension. Sedimentation of ash will continue until the overflow level at the top of the pipe is reached, whereupon sewage will be spilled into Waitemata Harbour. Once this has occurred, the accumulation of ash will be difficult to remobilise. Depending on how much ash is present, and the ratio of sewage or effluent to ash, it may be necessary to manually dig out the lower reaches of this section of the wastewater system. If the sediment-water ratio of the pumps is not exceeded, and they are able to move the sewage-ash mix this will result in severe abrasion to the pumps. Ensuing repairs may still be more cost effective than manually removing large volumes of sediment.

6.7.3.2 Newmarket control room

The Watercare control room in Newmarket is designed to monitor pump station status and respond to alarms. Although some pumps can be controlled from here, under normal conditions control is automatically managed locally at pump stations by a programmable logic controller (PLC). The Newmarket control room is manned 24 hours a day 365 days per year. In the event of communications failure with the pump stations, the control room's central location would allow for rapid manual assessment of any problems.

6.7.3.3 Mitigating impacts of direct ashfall on the network

Aside from ashfall entering stormwater drains (discussed in section 6.7.1.1), impacts of direct ashfall on the network relate to how well pump stations cope with ashfall. Procedures to mitigate these effects include:

- Sweeping pump station roofs clean before ash thicknesses exceed 10 cm to prevent roof damage or collapse.
- Installing filters on air vents to minimise ash ingress (provided the air is not fan assisted, in which case filters will quickly block).
- Sealing gaps around windows/doors.
- Cleaning communications equipment of excess ash
- Turning off wet-well bubblers to prevent compressors ingesting ash.

6.7.4 Treatment plant Impacts - Ash arriving through the system

Mangere's waste water treatment plant processes waste from most of the Auckland region from Auckland City to Papakura (see figure 6.17). In the absence of pump station failures, large quantities of ash may reach the processing plant through the sewage reticulation system, specifically the Eastern Interceptor. Three main sewerage lines combine at the Mangere plant in a receiving chamber, before mixing and entering the plant. Sewage and ash from the Eastern Interceptor would combine here with (largely) ash free sewage from the Western and South Western Interceptors.

Processing takes place in three main stages, divided into primary, secondary and tertiary treatments.

Primary treatment processes

Primary treatment involves screening any material coarser than 3 mm, before the waste flows through 12 aerated grit tanks to reduce flow velocity and lessen the buoyancy of particles. This process will remove much of the coarse ash that manages to reach the treatment plant; however significant amounts of fine ash will still pass this stage, as will the potentially acidic leachates associated with the ash. Furthermore the volumes of ash arriving through the system may be sufficient to overload the grit tanks faster than they can be emptied, resulting in more ash bypassing this process.

From the grit tanks the effluent progresses to the primary sedimentation tanks, where flow velocity is reduced and slowed, allowing solids to settle out of suspension over a 2 hour period. Sewage sludge (and ash) that are collected at this stage would then be scraped into hoppers and discharged into gravity thickener tanks. The sedimentation tank scrapers will likely be subject to accelerated wear after scraping large volumes of ash off sedimentation tank floors. The fluids pass over outlet weirs, and are pumped through the interstage pump station to the reactor/clarifiers. These pumps will also be subject to accelerated abrasion from ash (in total there are over 160 pumps on site at Mangere, all of which will be subject to accelerated wear).

The gravity thickener tanks mix up the solids, decanting off more fluid to the reactor/clarifiers. Settled sludge at a consistency of 6% solids is pumped to the anaerobic sludge digesters. Both reactor/clarifiers and sludge digesters are secondary treatment processes.

Secondary treatment processes

Anaerobic sludge digesters heat sludge to 37^{O} C to break down organic material, eventually converting it into methane. This process takes 15 days, during which the solids content is reduced to 4%. Ash will not break down in this way, and would simply take up space in the digesters.

Nine reactor/clarifiers are on site at Mangere, each with a diameter of 77 metres (figure 6.23). Within these systems bacteria strip out organic pollutants. This process is currently the most widely used sewage treatment process worldwide (Watercare, 2009). The balance of the pH in this process is critical though; should the pH fall below 6.5 bacterial conversion of nitrate(s) into nitrogen ceases. Any influx of ash into the treatment plant will likely be accompanied by highly acidic leachates. Although Watercare carefully balance pH, as under normal circumstances acidic effluent enters the system, ash leachates will potentially have sufficient volume and acidity to overwhelm countermeasures taken to increase the pH in the reactor/clarifiers.

Figure 6.23: Reactor/clarifiers at Mangere wastewater treatment plant

Solid waste discharged from the reactor/clarifiers is next treated by dissolved air flotation, whereby compressed air is mixed with the solids. The resulting bubbles cause effluent solids to float on the surface of the tank, where they are collected by a rotating arm. This process has not been tested with volcanic ash; its reaction to this process is unknown. However, depending on their composition and vesicularity, ash grains are likely to be heavier than organic particulates, especially during a localised basaltic eruption. Dense particles would inhibit flotation, possibly resulting in an accumulation of ash on the floor of the tank.

The final secondary process takes place in the dewatering plant. Extracted solids are “spun dry” in centrifuges, with the addition of polymers to aid flocculation of effluent. How well the flocculation will work in the event of an eruption would depend on the ratio of ash to effluent. Solids are removed from this process and disposed of as landfill.

Tertiary treatment processes

Tertiary treatment involves 2 processes. Liquid effluent from the reactor/clarifiers is pumped to a filtration facility. This consists of beds of granular anthracite, which remove particles down to 15 microns. Filters are cleaned daily, backwashing using recycled water and compressed air. This would need to occur more frequently if ash was to arrive through the system in large volumes. Fine ash will pass through the filters, and progress onto the final treatment, ultraviolet disinfection.

The ultraviolet disinfection process involves passing wastewater through 12 parallel channels, along which arrays of UV lamps are arranged in rows. The lamps are submerged lengthways along the direction of flow, and are encased in quartz tubes (figure 6.24).

Figure 6.24: UV disinfection facility at Mangere wastewater treatment plant (left). Quartz tubes used to protect UV lights (right)

These lamps are designed to achieve a 10000x reduction in the amount of pathogens discharged from the treatment plant. The presence of fine volcanic ash particulates within the effluent at this stage would increase it's turbidity, reducing the effectiveness of the UV disinfection process. Furthermore the tubes are periodically self cleaned by a surrounding rubber wiper ring. This cleaning process has the potential to scratch the tubes as ash is wiped along them. This is especially so in the event of an eruption from the Taupo Volcanic Zone or Taranaki, as these eruptions are likely to be andesitic, dacitic (or in a worst case scenario rhyolitic), and thus will contain quartz. In the event of a local explosive eruption from the AVF, predominant minerals found in the ensuing basaltic volcanic ash will include feldspars, pyroxene, and olivine. These minerals are all slightly softer than quartz, though olivine can at times be of equal hardness (7). Scratching of the quartz tubes would thus be possible, but would take place over a longer term, and would be less intense than if large quantities of silicic ash were passing through the system.

6.7.4 Mitigating impacts of ash arriving through the network

Following tertiary treatment the liquid effluent is discharged into Manukau harbour. Should large amounts of fine volcanic ash (<15 µm) manage to get this far, this would likely result in excess sedimentation at the outflow, which could need dredging. However this scenario is more likely to occur if the plant or parts of the plant are bypassed. Since at almost all stages of the treatment process ash has the potential to disrupt treatment or damage equipment, a partial or complete bypass of the treatment plant would be the best course of action. Although bypassing the plant would result in raw sewage being discharged into Manukau harbour, it would only be for the duration of the ashfall or while ash was present on the ground in central Auckland. If large volumes of ash entered the plant, the ensuing damage to plant components would likely result in long periods in which the plant would be inoperable, resulting in longer term discharge of untreated effluent into the harbour. In the event of a complete or partial plant bypass the large amounts of sediment that would enter the harbour would need to be moved to deeper water to prevent a large build up of sediment and untreated effluent around the outlet.

Instead of bypassing the treatment plant, sewage and ash could alternatively be discharged into Waitemata Harbour at Orakei. This option has significant advantages. It would prevent most ash reaching Mangere through the wastewater system, as the network preceding this pump station is the only shared sewerage and stormwater network. Untreated sewage would be spilled into Waitemata Harbour, this would allow the plant to keep processing waste from other areas of Auckland; those served by the Eastern, Western and South Western interceptors – these are not part of the shared network of sewage and stormwater. In this way the amount of untreated waste to be discharged into the environment would be reduced by 70%. In this instance dredging would be necessary at the overflow point at Orakei to remove ash from the outflow area.

If insufficient amounts of ash are coming through to justify discharge into Waitemata harbour or bypass into Manukau harbour, there are several courses of action that can be taken to ensure damage is minimised or recovery is hastened. Many of these steps involve pre-planning, and assume advance warning of an eruption is given.

- Biosolid disposal requires stabilisation with lime. The amount of lime required will likely significantly increase due to the potential acidity of volcanic ash. Much larger than usual stocks of lime will therefore be required.
- Reactor/clarifiers are highly sensitive to pH changes, and should be bypassed.
- Tertiary treatment processes should be bypassed to preserve filters and UV light tubes.
- Excess sedimentation is likely at the discharge point in Manukau Harbour; a dredge will need to be ready to clear this if necessary.
- With ash entering the system abrasion of components such as pumps will increase. Abrasion is particularly severe for pump impellers due to the speed at which they move. Spare impeller blades kept onsite will minimise repair times.
- Staff availability could be compromised if ashfall has closed roads, or staff need to be at home preserving their own property/looking after families. Contingency plans are required for this eventuality.

6.7.5 Direct ashfall on wastewater treatment facilities

6.7.5.1 Tephra loading

Heavy ashfall landing directly on the Mangere waste water treatment plant could be disastrous for many of the flat roofed structures present. Amongst others these include the screens building, co-generation plant, UV disinfection plant, biosolids dewatering building and alkaline stabilisation plant buildings. Office buildings and the control rooms also have flat or only slightly inclined roofs. Collapses of or heavy damage to commercial structures of this nature is more likely to occur than residential building collapse, due to the large roof spans involved in commercial and industrial buildings. This has been seen to occur in the past during medium to heavy ashfalls in various eruptions. For example, building damage in Rabaul during the 1994 Rabaul eruption was severe, as tephra loads were at times in excess of 7 kPa. Steel framed buildings performed particularly poorly, some even collapsed under loads just over 2 kPa, or around 150 mm of tephra (Blong, 2003). Collapses of large span buildings following ashfall from the 1991 Pinatubo eruption in the Philippines also occurred, with much less ash impacting them. Buildings such as hangars and warehouses at Clark air force base collapsed under ~150 millimetres of ash, while residential houses nearby survived relatively intact (Casadevall et al., 1996). The variety of buildings and construction types present at Mangere treatment plant will result in several different thresholds for the amount of ash required to damage or collapse roofs and walls. Where possible ash should be cleaned off large span roofs before more than 5 centimetres or so has accumulated. If more than 10 cm has accumulated such buildings should not be entered due to the risk of roof collapse.

The primary sedimentation tanks, anaerobic sludge digesters and gravity thickeners are all roofed. There is a lack of data on the effects of loading on these types of structures. Rapid removal of ash during any ashfall over 5 cm thick would be advisable. Due to the irregular shape and corrugations of the gravity thickener roof, ash will likely prove laborious to remove from this structure (figure 6.25).

Figure 6.25: Gravity thickeners at Mangere wastewater treatment plant (Watercare, 2009)

6.7.5.2 Ash leachates and acid rain

Acidic ash leachates and acid rain will not only cause corrosion to exposed metal infrastructure, but alter pH levels in the 9 reactor/clarifiers. Each of these units is made up of a series of eight compartments – four aerobic compartments which are aerated, and four anoxic. Under aerobic conditions, biochemical oxygen demand is reduced and ammonia is converted to nitrate and nitrites. Under anoxic conditions, bacteria convert the nitrate and nitrites into harmless nitrogen gas. Should the pH fall below 6.5 bacterial conversion of nitrate(s) into nitrogen ceases, and this type of treatment ceases to function. The reactor/clarifiers each have a diameter of 77 metres, and are open to the sky. They are therefore capable of collecting a lot of ash or acid rain. Once this occurs, pH changes are likely. The pH levels will therefore need to be continuously monitored and countered.

6.7.5.3 Ash ingress to structures

The control room for the plant relies heavily on air-conditioning; cool air is essential for the operation of the computer systems that control the plant. Research discussed in chapter 3 suggests that light ashfall would not be problematic for air-conditioning units. The control room cooling should therefore be adequate in light ashfall, however the same testing indicated that ashfall reaching a thickness of over 30 mm could potentially start to cause air-conditioning failure. This could be avoided by regular cleaning of the air-conditioner condensers during ashfall.

Although the control room uses air-conditioning, the interstage pump station distributed control system (DCS), and switchgear for the odour control fans are housed in other buildings which only use unfiltered fresh air vents and fans. These are situated in the ceilings of the rooms that house this equipment, and often directed at that equipment (figure 6.26). This creates a vulnerability even to light ashfall, as this would result in the ingress of ash into these buildings.

Figure 6.26: Switchgear for the DCS (left) and odour control beds (right). Note the air vents directly above the DCS cabinets.

Odour control fan switchgear cabinets are well sealed; ash around these would simply make a mess, and possibly cause minor corrosion to cabinets. DCS switchgear cabinets are vented. Ingress of ash into these cabinets ash will have the potential to cause electrical shorts. This is more likely to occur with damp ash, as ash becomes conductive when wet (Gordon et al., 2005). As these cabinets generate a lot of heat, ash would quickly dry, lessening the chance of shorts occurring. Ash inside the cabinets is still not desirable; apart from the (low) chance of electrical shorts, corrosion is possible in the longer term, and abrasion or binding of moving parts (e.g. switches) will be likely.

Compressed air is used in a variety of functions at Mangere. Grit tanks, dissolved air flotation tanks and reactor/clarifiers all require aeration. Ingestion of ash into compressors is likely to cause blockages in nozzles and damage seals. In the long term it may cause internal corrosion. The amount of damage that occurs depends on how well building are sealed, and whether compressors are operated while ash is falling. Ideally the processes which use compressed air would be bypassed during ashfall, however the primary grit tanks would be far less effective without the injection of compressed air, increasing the amount of solids to enter the rest of the plant.

Ash entering the reactor/clarifiers will not only alter pH levels, but may either accumulate in the base of the units, or be pumped through the system to tertiary treatment, depending on its buoyancy (largely an effect of grainsize).

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6.7.5.4 Power failure

In the event of power failure, on site generators can run the plant at up to 50% capacity. Some treatments are not used as a result. There are two forms of onsite power. Two backup generators run on diesel (figure 6.27) but the plant also has Four Jenbacher JMS 616 turbo-charged gas engine/generators. These produce almost 7 MW in total, and run on biogas produced by the anaerobic digesters. They are also able to run on natural gas as a backup. These generators will be useful in the event of power failure caused by ashfall in other locations, but may be slightly compromised in the event of direct ashfall on the plant. This is due to the need for air for combustion; the constant supply of air required means that air filters are likely to be blocked as ash is ingested. The generators will require regular maintenance and filter cleaning in this instance.

Figure 6.27: Back up generator and fuel supplies at Mangere treatment plant

6.7.5.5 Mitigating impacts of direct ashfall on the plant

During light ashfall directly on the plant, several operations at the Mangere treatment plant may be able to continue functioning, albeit with increased maintenance and careful management. Steps taken to ensure the plant keeps running include:

- Generators, pump motors and other machinery (such as the centrifuges) will need to be cleaned of ash, preferably with compressed air, but even careful brushing will help. Air-filters on motors/engines should be cleaned at least daily
- Compressors should be shutdown during ashfall to prevent the ingestion of ash
- Reactor/clarifier operation may need to temporarily cease as ash will drastically change pH, and subsequent tertiary processes will be subject to abrasion and blockages from ash mixed with effluent. If reactors keep functioning subsequent processes should be bypassed. In this instance the pH will need to be carefully monitored and balanced
- Air conditioning unit condensers (present at the control room building and offices) will gradually block up with ash, causing a drop in performance, and ultimately overloading the compressor. Condensers need to be cleaned out with compressed air or at least a soft brush when compressed air is unavailable. This will need to take place in breaks in ashfall if compressed air is used.
- DCS (distributed control system) cabinets for the interstage pump station may ingest some ash as exterior air is blown on to them. Exterior fans should be switched off during ashfall to minimise the amount of ash drawn into the building. Filters are unlikely to help as they will quickly block up. Any ash that manages to enter the cabinets should be removed as soon as possible by vacuuming.
- Exposed metals will be subject to rapid corrosion in the presence of moisture, and should be cleaned of ash as soon as possible.
- Flat and low pitch roofs at the Mangere treatment plant will need to be cleared of ash if tephra thicknesses exceed 5 cm. It should be noted that ash is very slippery, especially when wet. Large span roofs are especially at risk of

collapse from excess load, and should be cleaned first. If more than 10 cm thickness of ash is present on large span roofs the danger of collapse will be great enough that until inspected and cleared by a suitably qualified engineer, the buildings should not be entered. In this situation roof cleaning should not take place unless equipment such as cranes or cherry pickers that allow cleaning to take place without workers being supported by the roof top is used.

- Doorways and entrances to buildings that are not in use should be kept closed and sealed with duct tape or similar where possible. Using the entrance to the control room should be kept to a minimum to prevent excess ash being dragged in from outside.

During a light ashfall impacting Mangere, most operations will still be possible, theoretically allowing waste treatment to continue in the event of a local eruption. This would depend on whether or not ash was arriving through the reticulation network from central Auckland. To prevent this from occurring it will be necessary to divert sewage from the shared network to overflows at or before pump station 16 (soon to be replaced with PS 64).

In the event of a heavy ashfall sufficient to cause structural damage to large span buildings, it is likely that evacuations would have taken place in Auckland. This would greatly reduce the amount of sewage entering the system, and ultimately the quantity of untreated effluent being discharged into the ocean.

6.8 Summary

Stormwater systems are subject to influxes of volcanic ash during ashfall, and are therefore vulnerable. When stormwater and sewerage systems are shared ash may enter wastewater treatment plants though the reticulation network. Analysis of Auckland’s wastewater treatment plant at Mangere has identified vulnerabilities in the plant that would result in significant damage to processing capability in the event of large quantities of ash reaching the plant through the reticulation network. Therefore discharge of waste from the shared network at Orakei is recommended in the event of significant ashfall. This would result in the comparatively short term discharge of

30% of Auckland’s stormwater, ash and untreated sewage into Waitemata harbour. Failure to prevent ash reaching the plant would likely result in severe damage to treatment facilities from the high ash loads processed. This would result in plant shutdown and longer term discharge of all of Auckland’s untreated effluent would result until facilities were repaired or replaced.

Bypass of any treatment facility, or at least of secondary treatment facilities is recommended for any wastewater plant. Pump testing has illustrated the extreme wear possible in a short time from processing volcanic ash. Therefore even if treatment facilities are bypassed, damage may still occur within reticulation systems. Blockages of stormwater systems and sediment traps will need to be cleared after ashfall, whether or not they are shared with sewerage networks. Consequently, even without physical damage occurring, financial impacts are inevitable from ashfall, due to the requirement for increased maintenance following the event. Careful management of the response will minimise these impacts.

CHAPTER 7: SUMMARY & CONCLUSIONS

7.1 Summary

Lifelines do not stand alone; they are interconnected components of a functioning community. Frequently the extent of this interconnectivity is such that failure of one compromises several others. Telecommunications networks, airports, wastewater treatment plants, and water supplies are all dependant on electricity. Even transport networks are affected by electricity failures as traffic signals, street lighting etc require electricity. Temporary backup power in the form of batteries or generators is available for most vital infrastructure, but this is usually only sustainable for a number of hours, and often at reduced capacity. Roads are necessary for utility providers to physically access their distributed, operational infrastructure for maintenance and repairs. Airports and aircraft frequently support other lifelines as critical transport hubs in the supply of labour, parts and equipment. Telecommunications enable remote control and or monitoring of other network components such as wastewater pump stations. These examples illustrate how lifelines rely heavily upon each other; failure or severely reduced capacity in one sector can place others under strain and may even result in a cascade of failures. Consequently, resilience is requisite for all lifelines.

This research sought to assess the risks posed to lifelines infrastructure from volcanic ashfall, through a vulnerability analysis of selected infrastructure to volcanic ash. The areas researched were selected for the reasons outlined in section 1.2 – they represent essential lifelines and services in New Zealand, about which there is insufficient knowledge to quantify risk. What they have in common is that they are all types of infrastructure whose failure will both directly and indirectly affect everyone in not just the afflicted region, but in all of New Zealand.

7.2 Telecommunications and volcanic ash

The vulnerabilities of telecommunications infrastructure have been shown to vary depending on the amount of ashfall. Problems associated with light ashfall are not attributable to direct impacts on the telecommunications infrastructure itself, but instead from the potential power loss associated with ashfall. However, heavier ashfall exceeding ~30 mm does pose problems. These largely relate to the need of modern communications equipment for constant cooling. Awareness of the potential for certain types of air conditioners to not only lose performance, but possibly fail once ashfall has exceeded ~30 mm, is vital for managing the impacts of ashfall on urban and cell phone exchanges. The capacity to address this issue during ashfall needs to be addressed in any telecommunications company's response plan. Also required is the need to acknowledge that access to infrastructure sites, including the ability of staff to get to work, is largely dependant on vehicles having the ability to drive over ash covered roads. Planning and mitigation of ash risks is necessary to avoid costly damage from ash ingress to equipment. Potential risk management activity includes establishing the ability to disable fresh air intakes that would otherwise automatically turn on, cleaning air conditioner condensers before failure occurs, or getting staff to exchange roofs that are threatened by tephra loading.

The loss of communications networks even for short periods of time cause significant social disruption, anxiety and economic loss. The general public becomes effectively cut off from access to emergency services. Furthermore other lifelines providers may rely on remote access to their infrastructure. By identifying the vulnerabilities to ashfall inherent in telecommunications infrastructure, this research enables telecommunications providers to increase the resilience of their networks in the event of volcanic ashfall. This in turn benefits all end users of telecommunications – everyone. The outcomes of this research in the context of the "4 R's" of emergency management are presented in table 7.1.

Issue Identified	Reduction	Readiness	Response	Recovery
Vulnerability to power loss, & likelihood of this occurring		Network providers may prepare generators or extra batteries for key sites	Take backup generators or batteries to site	
Robustness of most telecoms infrastructure to light ashfall (excepting power loss).			Response to focus on vulnerable infrastructure.	
Vulnerability of cooling systems for all exchange types	Identification of what one of the key issues will be for telecommunications infrastructure providers during ashfall	This knowledge allows plans to be made by infrastructure providers for an ashfall event	Creating a small shelter directly over intakes will increase the robustness of units. Regular cleaning of condensers will enable cooling to continue in most ashfall events.	Continued cooling during ashfall will help preserve communications systems that will be necessary during and after the event.
Determination of threshold for failure of cooling systems		Plans can be created for different ashfall scenarios	Focus on sites receiving > 30 mm of ashfall.	
Automatic engagement of fresh air fans in cell sites	Creating a remote override for this function will negate problem	If no remote override is created then plans may be made to manually turn off these fans where ashfall is imminent.	Switching off these fans will preserve internal components of cell sites from direct damage from ash.	Cell sites will be functional soon after the ashfall rather than needing lengthy repairs.
Manual reset of compressors on air-conditioning units if condensers block.		Include contingency plans for this in ash response plans.	Technicians will need to be on site at exchanges to restart should this occur.	
Fresh air intakes on urban exchanges will ingest ash then filters will block.		Reliance on these intakes to be avoided		
Ability of staff to reach affected sites		Plans may be made for getting staff to affected sites in ashfall	4wd vehicles may be required	

Table 7.1 Key findings of this research for the vulnerability of NZ telecommunications infrastructure to volcanic ashfall

7.3 Air conditioners and volcanic ash

Although not a lifeline, the widespread dependence of infrastructural components on cooling has made air conditioner vulnerability a critical element in assessing lifelines resilience. Prior to testing, the few existing accounts of air-conditioner performance during ashfall were inadequate to extract meaningful information regarding performance under different eruption scenarios. Experimentation has demonstrated that airspeed and fan configuration has significant influence on the robustness of air conditioners during ashfall. A maximum failure threshold of 30 mm of ash for common split system air conditioner types has been established. Exceeding this is likely to cause sufficient blockages in the condenser that compressor damage and shutdowns may occur. This experimentation is important not only in that it has established expected failure thresholds, but more critically it has determined that operation remains viable during ashfall, provided monitoring and regular maintenance are carried out. Air conditioners may even support continuous operation if regular cleaning of units takes place. Consequently, infrastructure that relies on this type of cooling need not cease functioning as a result of ashfall (provided back up generators are available in the event of power loss). For users of infrastructure such as cold stores this means that the costly removal of goods prior to or during an eruption is not as urgent a task as previously thought. The main outcomes of this research are presented in table 7.2.

Issue Identified	Reduction	Readiness	Response	Recovery
Vulnerability of cooling systems / failure mechanism established	Identification of this issue allows steps to be taken to reduce future damage – through planning options or installing more robust types of unit with faster airflow.	This knowledge allows plans to be made by infrastructure providers to protect and maintain critical air conditioners before and during an ashfall event.	Creating a small shelter directly over intakes will increase the robustness of units. Regular cleaning of condensers will enable cooling to continue in most ashfall events.	Continued cooling during ashfall will help preserve infrastructure that relies on artificial cooling, reducing recovery time
Determination of threshold for failure of split system air conditioners.		Plans can be created for different ashfall scenarios.	Focus on sites receiving > 30 mm of ashfall. Units can still function in light ashfall.	
Viability of air conditioners in light ashfall			Continue to operate units in light ashfall where required	Goods and infrastructure that may have been spoiled or damaged due to air conditioners being turned off during light ashfall need not be: less damage to recover from.
Manual reset of compressors on air-conditioning units if condensers block.		Include contingency plans for this in ash response plans.	Technicians will need to be on site at exchanges to clean condensers and restart should this occur.	
Ineffectiveness of filtration on fresh air vents.		Reliance on these intakes to be avoided.	Turn off fans for external air vents.	

Table 7.2 Key findings of this research for the vulnerability air-conditioners to volcanic ashfall

7.4 Airports, aircraft and volcanic ash

In assessing airport vulnerabilities, the aim of this work was to determine best practice methodologies for mitigating the impacts of ashfall on airport infrastructure and grounded aircraft, and the potential for corrosion and abrasion on aircraft surfaces, by testing aircraft alloys with ash and acidic leachates. This research has augmented previously published accounts of ashfall impacts on the aviation sector. The analysis of the experiences and procedures of the two airports that have experienced the most frequent exposure to ashfall internationally over the last decade has helped to establish appropriate practices.

The testing of ash and leachates on aircraft surfaces has quantified a risk that has yet to be realised, but is nevertheless a strong possibility following ashfall on airports; rapid pitting corrosion on exposed aluminium or alloy surfaces. This research is contributing to considered risk management by New Zealand's aviation sector directly through a response plan prepared for Auckland Airport and Air New Zealand (included as appendix 2). This research has also contributed to a poster detailing appropriate steps to take in the event of an ashfall affecting airports. The poster, prepared in conjunction with New Zealand's Civil Aviation Authority, Air New Zealand, Auckland Airport and GNS Science, has been distributed to airports in the North Island (included as appendix 3). This provides ready access to mitigation options for reducing the impacts of ashfall on airports and aircraft. It also details where to look for further information, allowing rapid response to volcanic emergencies.

In 2007 Auckland Airport alone was estimated to contribute ~$19 billion to the NZ economy, 13.7% of New Zealand's GDP (Auckland International Airport, 2007). This contribution is equivalent to over $50 million per day. Disruptions for Auckland Airport due to ashfall would therefore have a significant effect on the New Zealand economy, the consequences of which would affect all New Zealand residents – not just those directly impacted by ashfall. An increase in the resilience of Auckland Airport would thus pay dividends when ashfall impacts Auckland. As demonstrated in chapter 4, the financial outlay required to do this is minimal, but the benefits are potentially substantial. Implementation of these measures will enable the airport to recover more quickly from such an event. The faster resumption of services will reduce losses to all airport users, and the greater NZ economy. In addition a functioning international airport close to the site of a major catastrophe will allow a more direct route for any required overseas aid (ash plumes permitting). The outcomes of this research in the context of the "4 R's" of emergency management are presented in table 7.3.

Issue Identified	Reduction	Readiness	Response	Recovery
Quantification of corrosion from ash leachates on grounded aircraft		Plan to remove, or if not possible protect and quickly clean aircraft exposed to ashfall	Concentrate on cleaning exposed metal surfaces, especially if light rainfall occurs	Rapid and effective response during the event will prevent the need for extensive repairs post event.
Protective procedures for aircraft exposed to ashfall	The current methodology of covering vulnerable parts of aircraft with tarpaulins/plastic sheeting has been shown to be effective	Stockpiling appropriate materials to cover aircraft is advisable.	The current methodology of covering vulnerable parts of aircraft with tarpaulins/plastic sheeting has been shown to be effective	
Clean up methodologies – aircraft	Identification of best practice methodologies for removing ash that do not damage aircraft.		Hosing and careful sweeping of ash will in most cases be sufficient to clean aircraft surfaces.	
Clean up methodologies and operational procedures – airports		Equipment required and methods for cleaning ash from airports established.	More precise methods for cleaning ash from airports established.	Faster recovery for an airport in an affected site allows outside aid to reach the afflicted area sooner.
Clean up timeframes		Timeframes for different methods of cleaning runways and paved areas have been established, enabling more accurate response planning.		

Table 7.3 Key findings of this research for the impacts of volcanic ash on airports and grounded aircraft.

7.5 Vehicle mobility on ash covered roads

Using vehicles on ash covered roads is necessary during and/or after volcanic ashfall in affected areas. Establishing the depths at which ash may become problematic for driving different classes of vehicle is a necessary pre-requisite for efficient response to any volcanic eruption generating more than a few millimetres of ash fall. Testing conducted for this thesis has taken steps towards establishing thresholds for ash depths that can confidently be driven through, on different slopes and with different vehicle types. These findings can assist in determining appropriate vehicle types to be used and routes taken by emergency services, lifelines infrastructure providers, and other utility companies. They are also useful for evacuation planning, determining whether the general public will be able to use their own vehicles in different scenarios. Access to this information enables better planning for response to ashfall by all road users. For infrastructure management this may involve placement of four wheel drive vehicles in strategic locations or with technicians prior to an anticipated ashfall. In addition to response planning, entities such as councils, Transit New Zealand and roading contractors can also use this information to help prioritise the removal of ash from roads and inform the public of the current hazards that ash presents along routes. These findings will assist responders to improve their planning for ashfall, and will ultimately allow a more efficient response to such an event. The main outcomes of this research are presented in table 7.4

Issue Identified	Reduction	Readiness	Response	Recovery
Approximate thresholds for safe driving on ash covered roads in different vehicle types.		Planning for evacuation methods and suitable vehicle types enabled. All agencies involved can consider these effects on vehicle mobility when planning their response.	Use of 4wd vehicles will improve response by emergency services and infrastructure providers. The likelihood of having vehicles stuck is decreased.	
Approximate thresholds for safe driving on ash covered roads of differing gradient		Planning for evacuation routes, methods and suitable vehicle types enabled. All agencies involved can consider these effects on vehicle mobility when planning their response..	The flattest possible route choice and use of appropriate vehicles will improve response by emergency services and infrastructure providers.	

Table 7.4 Key findings of this research for the impacts of volcanic ash on vehicle mobility

7.6 Wastewater systems and volcanic ash

Sewerage systems will only be subject to large influxes of volcanic ash if they share reticulation networks with stormwater systems. This is the case in many cities, including central Auckland. Testing during this research has demonstrated that pump impellers will be subjected to vastly accelerated wear when pumping volcanic ash. Analysis of Auckland's wastewater treatment plant at Mangere has identified many more vulnerabilities in the plant itself, such that complete bypass of the plant is recommended in the event of significant ashfall. While this would result in the discharge of stormwater, ash and untreated sewage into Waitemata harbour, the duration would be limited to the period during which ash covered impermeable surfaces, and is preferable to the longer term discharge of untreated effluent that would result from treatment plant damage by processing high ash loads. Furthermore, provided ashfall was not directly impacting the plant itself, treatment of 70% of Auckland's waste could continue in the presence of ash on the ground, as only 30% of Auckland's reticulation system is shared with stormwater, and this can all be diverted before reaching the treatment plant.

Awareness of the vulnerabilities of Auckland's reticulation network and treatment plant is vital for Watercare to create a viable response plan for volcanic ash. In bypassing the treatment plant or even processes within the plant during ash ingress to the system, the damage caused to both infrastructure and the environment can be significantly reduced. The likelihood of a significant environmental and health hazard occurring due to long duration discharge of untreated waste into the ocean is thus reduced considerably. The main outcomes of this research are presented in table 7.5.

Issue Identified	Reduction	Readiness	Response	Recovery
Plant vulnerability to direct volcanic ashfall established	Identification of some areas of vulnerability (such as cooling via fresh air vents) allows small changes to be made to infrastructure that will result in a significant reduction in potential damage.	Operational procedures for ashfall can be established based on the vulnerabilities identified.		
Plant vulnerability to ash arriving through the wastewater network established.	When used, bypass systems negate the issue of ash impacting waste processing plants.	Operational procedures for ash arriving through the network can be established based on the vulnerabilities identified.	Bypass the treatment plant if waste is contaminated with ash to avoid long term damage. For Auckland it will be necessary to discharge untreated waste into Waitemata harbour at PS 16/64 in the short term.	Continued operation of wastewater treatment facilities post event will allow the earlier return of evacuees and reduce environmental damage and health hazards caused by longer duration discharge of untreated waste into the ocean.
Pump vulnerability to ash and leachates	Vastly increased wear on pump impellers and components has been shown to occur when pumping ash even for short periods of time.	Planning to avoid use of pumps where possible is advisable, plus stockpile spare parts/impellers for essential pumps pre-eruption.		
Sediment trap vulnerability	Sediment traps will quickly reach capacity	Plans for frequent removal of material from sediment traps are necessary.		

Table 7.5 Key findings of this research for the impacts of volcanic ash on wastewater systems

7.7 Future Research

A number of future research areas have been identified as a result of the research completed in this thesis. Notably, further information is needed in order to more accurately quantify some of the vulnerabilities identified. In terms of telecommunications infrastructure, testing of rural exchanges in simulated ashfall would better predict performance during a volcanic eruption. For this study, the impacts of ashfall on the cooling of these cabinets were calculated by applying the results of air-conditioning and filter media testing from urban exchanges. Actual testing of this type of equipment would be preferable. Conducting this research would depend on the availability of rural exchange equipment. Telecommunications equipment in general is continuously evolving and frequently upgraded. Vulnerability testing needs to maintain pace with these changes to accurately reflect current risk exposure. Ideally radio signal attenuation during ashfall also requires testing, however this is not practical in a laboratory, and would need to be addressed during an eruption. Even then the differences in grainsize, ash concentration, electrical charge and moisture concentration would make comprehensive testing difficult. Access to broadcasting equipment that utilises different wavelengths would also be necessary.

Air-conditioner testing could be made more robust by extending testing to a wider variety of unit types. This is especially true of small scale air conditioners and heat exchangers such as those used in rural exchanges.

Vehicle mobility has been tested on dry ash covered roads, further testing in wet conditions would be useful, as would more tests on consolidated ash deposits. This needs to take place in the field on actual ash deposits. Grainsize is thought to have a significant effect on vehicle mobility in ash, this assertion needs to be tested during an eruption. It is unlikely that comprehensive vehicle mobility testing could be achieved in one study, but discrete tests and observations can easily be conducted concurrently with other field research that takes place during eruptions. A larger variety of vehicles will need to be tested in order to achieve more meaningful results.

Research on ashfall impacts on vehicles themselves is also required. Much information on this subject draws upon impacts suffered by cars during the 1980 Mt St Helens eruption. Automotive technology has changed markedly in the intervening decades. For example carburettors have been superseded by fuel injection. Petrol and diesel turbo charged engines with increased air intakes are now common, traction control systems are standard. Quantitative testing of vehicles in ashfall needs to be conducted to improve response planning.

7.8 Contributions to risk reduction

The resilience of a community is directly tied to the robustness of the lifelines on which the community relies on. Lifeline infrastructure providers therefore have a duty to effectively manage the risks faced by any foreseeable hazards. This research has been conducted with the support and cooperation of major stakeholders in lifelines infrastructure (Auckland Airport, Air New Zealand, WaterCare, Transit, Telecom and Chorus). The vulnerabilities quantified in this thesis give these stakeholders the necessary tools to develop effective risk management strategies to cope with hazards from volcanic ash, and thus increase their resilience. This information is being put to further use by being included in fragility functions being created for New Zealand's current *RiskScape* project, led by GNS Science and NIWA. These functions are used to determine potential losses in the event of the realisation of various types of risks. The loss information is in turn used to create a support tool to prioritize risk reduction measures, and improve risk management in New Zealand.

The outcomes of this work can be measured against the potential impacts of ashfall on New Zealand's lifelines should we fail to act to improve their resilience. These contributions to risk reduction are summarized in table 7.6, which describes the impacts of different amounts of ashfall on the infrastructure types investigated, depending on whether the findings of this thesis are implemented or not. It demonstrates that without the implementation of the mitigation methods described in this thesis, there is a corresponding increase in negative outcomes as ashfall increases.

	1mm Ashfall		10mm Ashfall		50mm Ashfall	
Outcome	Research findings implemented	No change from present	Research findings implemented	No change from present	Research findings implemented	No change from present
Telecoms	Possibility of power loss	Possibility of power loss	Likely power loss, larger numbers of backup generators and batteries available to increase exchange functionality. Communications failure still possible but for less time.	Likely power loss, exchanges run out of power in 2-12 hours depending on type. Communications failure.	Likely power loss, but effects lessened by increased backup. Cooling systems keep functioning, allowing exchanges to keep operating	Likely power loss, exchanges run out of power in 2-12 hours depending on type, air-conditioner failure leads to automatic exchange shutdowns and subsequent communications failures. Ash ingestion into cell and urban exchanges through fresh air intakes automatically switching on, damaging internal components and increasing required recovery time.
Air conditioners	No physical effect	No physical effect, unnecessary anxiety caused for those relying on air conditioners.	No significant physical effect, cleaning units required.	No significant physical effect, cleaning units required. Possibility of unnecessary removal of goods from cool storage	Air conditioners can continue to function effectively	Air-conditioner failure for split system type units. Cold-store goods spoil, infrastructure reliant on cooling fails.
Airports & grounded aircraft	Airport closure while ash plume is present and ash is on ground. No physical damage expected. Economic loss while airport is closed. Rapid cleanup ensures quick return to business as usual (BAU).	Airport closure while ash plume is present and ash is on ground. No physical damage expected if aircraft are covered. Economic loss while airport is closed. Cleanup takes longer than if operational procedures advised in this work are followed, increasing economic losses.	Airport closure while ash plume is present and ash is on ground. Little physical damage expected. Economic loss while airport is closed. Rapid cleanup ensures quick return to BAU.	Airport closure while ash plume is present and ash is on ground. Little physical damage expected if aircraft are covered. Some corrosion to aircraft skins may occur if cleanup of aircraft is not rapid. Cleanup takes longer than if operational procedures advised in this work are followed, vastly increasing economic losses due to airport closure.	Airport closure while ash plume is present and ash is on ground. Some physical damage expected to infrastructure and possibly minor damage to aircraft depending on leachate chemistry. Hangars preserved from collapse/damage if cleaned as ash falls. Economic loss while airport is closed. Effective cleanup ensures quickest possible return to BAU.	Airport closure while ash plume is present and ash is on ground. Physical damage expected to infrastructure, hangars may be damaged and possibly even collapse. Damage to aircraft. skins depending on leachate chemistry may occur if cleanup of aircraft is not rapid. Cleanup takes longer than if operational procedures advised in this work are followed, vastly increasing economic losses due to airport closure.
Roads	Slippery conditions, road markings obscured. Minor accidents ensue.	Slippery conditions, road markings obscured. Minor accidents ensue.	Slippery conditions, road markings obscured. Minor accidents ensue. Routes with steep hills avoided by emergency services and responders. Evacuation routes remain passable.	Slippery conditions, road markings obscured. Minor accidents ensue. Possibility of emergency responders and evacuees becoming stuck or held up on steep roads.	Slippery conditions, road markings obscured. Minor accidents ensue. Routes with steep hills avoided by emergency services and responders. Evacuation routes remain passable.	Slippery conditions, road markings obscured. Minor accidents ensue. Possibility of emergency responders and evacuees becoming stuck or held up on steep roads.
Wastewater	Increased wear to pumps. pH changes need addressing in reactor – clarifiers if ash not diverted.	Increased wear to pumps, pH changes need addressing in reactor - clarifiers	Damage to network pumps pre-outflow to sea. Large amounts of sedimentation in system upstream from outflow to sea Treatment plant damage avoided from ash arriving through network. Short term discharge of untreated effluent to sea. In Auckland’s case 30% of the entire city’s waste would be discharged without treatment while ash was on the ground in large quantities in central Auckland.	Damage to network pumps pre-outflow to sea. Large amounts of sedimentation in entire system, some causing blockages. Some treatment plant damage, possibly requiring days of shut down to effect repairs. In Auckland’s case this will result in all of Auckland’s waste being flushed into Waitemata and Manukau harbours. Many pumps require new impellers and seals.	Damage to network pumps pre-outflow to sea. Large amounts of sedimentation in system upstream from outflow to sea Treatment plant damage avoided from ash arriving through network. Short term discharge of untreated effluent to sea. In Auckland’s case 30% of the entire city’s waste would be discharged without treatment while ash was on the ground in large quantities in central Auckland.	Damage to network pumps pre-outflow to sea. Large amounts of sedimentation in entire system, some causing blockages. Significant treatment plant damage, requiring days to week of plant closure before repairs can be completed. During this time untreated waste is flushed out to sea causing environmental damage. In Auckland’s case this will result in all of Auckland’s waste being flushed into Waitemata and Manukau harbours until repairs are effected. Most pumps require complete overhaul.
Overall Outcome	Possible power loss may cause temporary communications interruptions, Brief airport closure, minor road accidents	Possible power loss may cause temporary communications interruptions, Longer airport closure, minor road accidents	Short term communications failures, Short term airport closure, minor road accidents, short term discharge of untreated effluent to sea.	Increased duration of communication failures, longer duration airport closure time and subsequent increase in economic losses, minor damage to aircraft, evacuees stuck on steep ash covered roads, response time for emergency services increases, damage to and temporary closure of wastewater treatment plants, longer term discharge of untreated effluent to ocean.	Short term communications failures, minor damage to airport infrastructure and aircraft, short term airport closure while ash is on ground, minor road accidents, short term discharge of untreated effluent to sea.	Communications failures and infrastructure damage, cold-store goods spoil, infrastructure reliant on cooling fails. Infrastructure and aircraft damage at airports, long duration closure time (up to days) post ashfall causing significant economic losses for NZ, emergency responders and evacuees stuck on roads. Significant damage to and temporary closure of wastewater treatment plants, longer term discharge of untreated effluent to ocean.

Table 7.6 Impacts of different levels of ashfall on infrastructural types studied, depending on the implementation of the findings of this thesis

The findings of this thesis are necessary to arm infrastructure providers with the tools to fully evaluate the risks posed by volcanic ash to their respective networks. The analyses conducted have identified several vulnerabilities to volcanic ash in our critical lifelines and infrastructure. In most cases only small physical or operational changes are required to mitigate the hazards caused by volcanic ashfall, recommended mitigation strategies have been given where appropriate to facilitate this process. Implementation of these changes will improve infrastructure assurance, not just increasing the organisational resilience of lifelines providers, but in turn increasing the resilience of the communities who rely on such infrastructure, benefiting not just infrastructure providers but all inhabitants of New Zealand By identifying vulnerabilities to ashfall and subsequent mitigation options in all of the areas studied, this research has significantly contributed to volcanic hazard planning and risk reduction strategies in New Zealand.

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APPENDIX 1. RESULTS OF AIR-CONDITIONER TESTING UNDER SIMULATED ASHFALL

Mitsubishi MWH 17KV

Unit Cooling Air, Dry Ash Passed Through Condenser

Time	Ash Added/rate of fall per hour	Total ash thickness equivalent	Cold Air Temperature (^{O}C)
0 minutes	0/0	0 mm	10.2
5 minutes	100 ml/2 mm	0.2 mm	10.2
10 minutes	100 ml/2 mm	0.4 mm	10.4
15 minutes	100 ml/2 mm	0.6 mm	10.4
20 minutes	100 ml/2 mm	0.8 mm	10.3
25 minutes	100 ml/2 mm	1.0 mm	10.4
35 minutes	100 ml/2 mm	1.2 mm	10.4
40 minutes	100 ml/2 mm	1.4 mm	10.6
45 minutes	100 ml/2 mm	1.6 mm	10.6
50 minutes	100 ml/2 mm	1.8 mm	10.6
55 minutes	100 ml/2 mm	2.0 mm	10.5
65 minutes	100 ml/2 mm	2.2 mm	10.6
70 minutes	100 ml/2 mm	2.4 mm	10.4
75 minutes	100 ml/2 mm	2.6 mm	10.4
Unit removed from casing, photographed (not cleaned), testing resumed next day.			
80 minutes	100 ml/2 mm	2.8 mm	10.4
85 minutes	100 ml/2 mm	3.0 mm	10.4
95 minutes	100 ml/2 mm	3.2 mm	10.4
100 minutes	100 ml/2 mm	3.4 mm	10.4
105 minutes	100 ml/2 mm	3.6 mm	10.6
110 minutes	100 ml/2 mm	3.8 mm	10.5
115 minutes	100 ml/2 mm	4.0 mm	10.4
125 minutes	100 ml/2 mm	4.2 mm	10.5
130 minutes	100 ml/2 mm	4.4 mm	10.4
135 minutes	100 ml/2 mm	4.6 mm	10.6
140 minutes	100 ml/2 mm	4.8 mm	10.4
150 minutes	100 ml/2 mm	5.0 mm	10.4
160 minutes	100 ml/2 mm	5.2 mm	10.4
165 minutes	100 ml/2 mm	5.4 mm	10.5
170 minutes	100 ml/2 mm	5.6 mm	10.6
175 minutes	100 ml/2 mm	5.8 mm	10.4
180 minutes	100 ml/2 mm	6.0 mm	10.5
Increase in rate of ashfall to 2.5 mm/hour			
190 minutes	250 ml/2.5 mm	6.5 mm	10.4
200 minutes	250 ml/2.5 mm	7 0 mm	10.4
215 minutes	250 ml/2.5 mm	7.5 mm	10.6
225 minutes	250 ml/2.5 mm	8.0 mm	10.5

240 minutes	250 ml/2.5 mm	8.5 mm	10.6
250 minutes	250 ml/2.5 mm	9.0 mm	10.4
265 minutes	250 ml/2.5 mm	9.5 mm	10.4
275 minutes	250 ml/2.5 mm	10.0 mm	10.6
360 minutes	0 ml/0 mm	10.0 mm	10.5
480 minutes	0 ml/0 mm	10.0 mm	10.5

Unit Producing Cold Air, Damp Ash + Water Spray Passed Through Condenser

Time	Ash Added/rate of fall per hour	Total ash thickness equivalent	Cold Air Temperature (^{O}C)
0 minutes	0 ml/0 mm	0 mm	10.4
5 minutes	100 ml/2 mm	0.2 mm	10.3
10 minutes	100 ml/2 mm	0.4 mm	10.3
15 minutes	100 ml/2 mm	0.6 mm	10.3
20 minutes	100 ml/2 mm	0.8 mm	10.3
25 minutes	100 ml/2 mm	1.0 mm	11.7
Unit removed from casing, photographed (not cleaned), testing resumed next day. The change in temperature is attributed not to ash but to slight differences in the reassembly of the unit – the most likely scenario is that the temperature sensor had moved slightly in relation to airflow			
30 minutes	0 ml/0 mm	1.0 mm	10.1
35 minutes	100 ml/2 mm	1.2 mm	10.2
40 minutes	100 ml/2 mm	1.4 mm	10.4
45 minutes	100 ml/2 mm	1.6 mm	10.4
50 minutes	100 ml/2 mm	1.8 mm	10.3
55 minutes	100 ml/2 mm	2.0 mm	10.4
65 minutes	100 ml/2 mm	2.2 mm	10.3
70 minutes	100 ml/2 mm	2.4 mm	10.3
75 minutes	100 ml/2 mm	2.6 mm	10.4
80 minutes	100 ml/2 mm	2.8 mm	10.3
85 minutes	100 ml/2 mm	3.0 mm	10.5
95 minutes	100 ml/2 mm	3.2 mm	10.2
100 minutes	100 ml/2 mm	3.4 mm	10.5
105 minutes	100 ml/2 mm	3.6 mm	10.2
110 minutes	100 ml/2 mm	3.8 mm	10.4
115 minutes	100 ml/2 mm	4.0 mm	10.4
125 minutes	100 ml/2 mm	4.2 mm	10.3
130 minutes	100 ml/2 mm	4.4 mm	10.4
135 minutes	100 ml/2 mm	4.6 mm	10.4
140 minutes	100 ml/2 mm	4.8 mm	10.5
150 minutes	100 ml/2 mm	5.0 mm	10.4

Unit Warming Air, Dry Ash Passed Through Evaporator

Time	Ash Added/rate of fall per hour	Total ash thickness equivalent	Warm Air Temperature (^{O}C)
0 minutes	0/0	0 mm	53.3
5 minutes	100 ml/2 mm	0.2 mm	53.3
10 minutes	100 ml/2 mm	0.4 mm	53.3
15 minutes	100 ml/2 mm	0.6 mm	53.4
20 minutes	100 ml/2 mm	0.8 mm	53.6
25 minutes	100 ml/2 mm	1.0 mm	53.8
35 minutes	100 ml/2 mm	1.2 mm	53.8
40 minutes	100 ml/2 mm	1.4 mm	53.9
45 minutes	100 ml/2 mm	1.6 mm	53.9
50 minutes	100 ml/2 mm	1.8 mm	53.7
55 minutes	100 ml/2 mm	2.0 mm	53.6
65 minutes	100 ml/2 mm	2.2 mm	53.6
70 minutes	100 ml/2 mm	2.4 mm	53.7
75 minutes	100 ml/2 mm	2.6 mm	53.6
Unit removed from casing, photographed (not cleaned), testing resumed			
75 minutes	0 ml/0 mm	2.6 mm	53.7
80 minutes	100 ml/2 mm	2.8 mm	53.9
85 minutes	100 ml/2 mm	3.0 mm	54.1
95 minutes	100 ml/2 mm	3.2 mm	53.7
100 minutes	100 ml/2 mm	3.4 mm	53.6
105 minutes	100 ml/2 mm	3.6 mm	53.3
110 minutes	100 ml/2 mm	3.8 mm	53.5
115 minutes	100 ml/2 mm	4.0 mm	53.5
125 minutes	100 ml/2 mm	4.2 mm	53.4
130 minutes	100 ml/2 mm	4.4 mm	53.3
135 minutes	100 ml/2 mm	4.6 mm	53.5
140 minutes	100 ml/2 mm	4.8 mm	53.5
150 minutes	100 ml/2 mm	5.0 mm	53.5

(Note the ambient temperature increase of 1 deg C during the first 30 minutes of this testing)

Unit Warming Air, Ash + Water Spray Passed Through Evaporator

Time	Ash Added/rate of fall per hour	Total ash thickness equivalent	Warm Air Temperature (^{O}C)
0 minutes	0/0	0 mm	53.5
5 minutes	100 ml/2 mm	0.2 mm	53.4
10 minutes	100 ml/2 mm	0.4 mm	53.1
15 minutes	100 ml/2 mm	0.6 mm	53.0
20 minutes	100 ml/2 mm	0.8 mm	52.6
25 minutes	100 ml/2 mm	1.0 mm	52.6
35 minutes	100 ml/2 mm	1.2 mm	52.6
40 minutes	100 ml/2 mm	1.4 mm	52.6
45 minutes	100 ml/2 mm	1.6 mm	52.5
50 minutes	100 ml/2 mm	1.8 mm	52.4
55 minutes	100 ml/2 mm	2.0 mm	52.3
65 minutes	100 ml/2 mm	2.2 mm	52.5
70 minutes	100 ml/2 mm	2.4 mm	52.8
75 minutes	100 ml/2 mm	2.6 mm	52.7
Unit removed from casing, photographed (not cleaned), testing resumed.			
75 minutes	0 ml/0 mm	2.6 mm	52.6
80 minutes	100 ml/2 mm	2.8 mm	52.6
85 minutes	100 ml/2 mm	3.0 mm	52.9
95 minutes	100 ml/2 mm	3.2 mm	52.8
100 minutes	100 ml/2 mm	3.4 mm	52.8
105 minutes	100 ml/2 mm	3.6 mm	52.6
110 minutes	100 ml/2 mm	3.8 mm	53.0
115 minutes	100 ml/2 mm	4.0 mm	53.0
125 minutes	100 ml/2 mm	4.2 mm	52.9
130 minutes	100 ml/2 mm	4.4 mm	52.7
135 minutes	100 ml/2 mm	4.6 mm	52.9
140 minutes	100 ml/2 mm	4.8 mm	53.0
150 minutes	100 ml/2 mm	5.0 mm	53.0

Toshiba testing – dry

Time (mins)	Room temp Celsius	Amount of ash added	Cold air temperature degrees Celsius	~ Equivalent depth of ashfall	Notes
0	21.7	0	10.3		
5	21.7	0	10.3		
10	21.7	100ml	10.4		
15	21.7	100ml	10.5		
20	21.7	100ml	10.7		
25	21.7	100ml	10.5	1 mm	
30	21.7	100ml	10.5		
35	21.3	100ml	10.6		
40	21.7	100ml	10.9		
45	21.7	100ml	11	2 mm	
50	21.7	100ml	11.1		
55	21.7	100ml	11.1		
60	22.1	100ml	10.8		
65	22.1	100ml	10.9	3 mm	
70	22.1	100ml	10.8		
75	22.3	100ml	10.8		
80	21.7	100ml	11		
85	21.7	100ml	11.1	4 mm	
90	21.7	100ml	11		
95	21.7	100ml	10.9		
100	21.7	100ml	11.1		
105	21.7	100ml	11.2	5 mm	
110	21.7	100ml	11.1		
115	21.7	100ml	11.2		
120	21.7	100ml	11.1		
125	21.1	100ml	11.1	6 mm	
130	21.1	100ml	11.1		
135	21.7	100ml	11.3		
140	21.7	100ml	11.4		
145	22.1	100ml	11.5	7 mm	
150	22.1	100ml	11.5		
155	21.7	100ml	11.1		
160	21.7	100ml	11		
165	21.1	100ml	11	8 mm	
170	21.2	100ml	11		
175	21.7	100ml	11.3		
180	21.5	100ml	11.3		
185	21.7	100ml	11.2	9 mm	
	End of testing for day	Unit photographed			Increased temp next day due to ash settling in condenser?
190	21.7	0ml	N/A		Unit turned on 1 hour before testing
250	21.7	0ml	12.1		
255	21.7	100ml	12.3		
260	21.3	100ml	12.5		

265	21.7	100ml	12.2		
270	22.1	100ml	12.8	10 mm	
275	22.1	100ml	12.9		
280	22.1	100ml	12.9		
285	22.1	100ml	12.8		
290	21.7	100ml	12.7	11 mm	
295	21.7	100ml	12.3		
300	21.7	100ml	12.5		
305	21.7	100ml	12.6		
310	21.7	100ml	12.6	12 mm	
315	22.1	100ml	12.6		
320	22.1	100ml	12.4		
325	22.1	100ml	12.3		
330	22.1	100ml	12.5	13 mm	
335	21.7	100ml	12.8		
340	21.7	100ml	13.2		
345	21.7	100ml	13		
350	21.7	100ml	13.1	14 mm	
355	21.7	100ml	13.1		
360	21.7	100ml	13.3		
365	21.7	100ml	13.1		
370	21.7	100ml	13.3	15 mm	
	End of testing for day				End of testing for day
375	22.7	0ml	N/A		Unit turned on 1 hour before testing
435	22.7	0ml	13.4		
440	22.7	100ml	13.5		
445	22.7	100ml	13.6		
450	22.7	100ml	13.6		
455	22.7	100ml	13.7	16 mm	
460	22.7	100ml	13.6		
465	22.7	100ml	13.6		
470	22.7	100ml	13.4		
475	22.7	100ml	13.7	17 mm	
480	22.7	100ml	13.4		
485	23.1	100ml	13.5		
490	23.1	100ml	13.3		
495	23.1	100ml	13.4	18 mm	
500					Top removed, unit photographed, top replaced
505	22.7	0ml	12.7		
510	23.1	100ml	12.6		
515	22.7	100ml	12.6		
520	22.5	100ml	13		
525	22.7	100ml	12.8	19 mm	
	End of testing for day			N/A	
530	22.1	0ml	N/A		Unit turned on 1 hour before testing
590	22.1	0ml	12.2		
595	22.1	100ml	12.1		

600	22.1	100ml	12.2		Visibly less ash is being entrained as blockages cause ash-laden air to be blown out of the back of the condenser
605	22.3	100ml	12.3		
610	22.1	100ml	12.5	20 mm	
615	21.9	100ml	12.9		
620	22.1	100ml	12.7		
625	22.1	100ml	12.4		
630	22.1	100ml	12.7	21 mm	
635	22.1	100ml	12.9		
640	22.1	100ml	13.1		
645	22.1	100ml	12.8		
650	21.7	100ml	12.6	22 mm	
655	21.7	100ml	12.7		
660	21.7	100ml	12.8		
665	21.7	300ml	12.6		Note increase in ashfall rate
670	22.3	300ml	12.7	24 mm	
675	22.3	300ml	13.1		
680	22.3	300ml	13.1		
685	22.3	300ml	13.4		
690	22.3	300ml	13.5	27 mm	Photographs
695	22.7	300ml	13.6		
700	22.3	300ml	13.7		
705	22.3	300ml	13.6		
710	22.7	300ml	13.2	30 mm	
715	23.1	300ml	13.3		
720	22.3	300ml	13.6		
725	22.3	300ml	13.4		
730	22.3	300ml	13.2	33 mm	
735	23.1	300ml	13.6		
740	23.1	300ml	13.5		
745	23.1	0ml	13.4		Checking how stable temperature was when no ash was added
750	23.1	0ml	13.4		
755	22.3	300ml	13.4		
760	22.3	500ml	13.4		
765	22.1	500ml	13.4		
770	22.1	500ml	13.5	39 mm	
775	22.3	500ml	13.7		
780	22.3	500ml	13.7		
785	22.3	500ml	13.7		
790	22.3	500ml	13.5	44 mm	
795	22.3	500ml	13.9		
800	22.3	500ml	13.7		
805	22.3	500ml	13.6		
810	22.3	500ml	13.6	49 mm	
815	22.3	500ml	13.7		

820	21.7	500ml	13.7	51.5 mm	
	end of testing for day				Top removed, unit photographed, top replaced
825	21.7	0ml	N/A		Unit turned on 1 hour before testing
885	21.7	0ml	12.1		
890	22	0ml	12.4		
895	21.7	0ml	5 minute shut down period 19.1		Unit shut itself down due to compressor overheating
900	21.7	0ml	18.1		
905	21.7	0ml	12.3		
910	21.7	0ml	12.3		
915	21.7	0ml	12.3		
920	21.7	0ml	12.4		
925	21.7	0ml	12.5		
930	21.7	0ml	12.4		
935	21.7	0ml	4 minute shut down period 19		Unit shut itself down due to compressor overheating
940	21.7	0ml	17.1		3 minutes following restart to reach within 0.3 degrees of previous temperature
945	20.7	0ml	12.4		
950	21.7	0ml	12.5		
955	21.7	0ml	4 minute shut down period 19.2		
960	21.7	0ml	15		
965	21.7	0ml	12.4		
970	21.7	0ml	12.2		
	End of testing for day				End of testing for day
975	21	0ml	N/A		Unit turned on 1 hour before testing
1035	20.7	0ml	11.8		
1040	20.7	500ml	11.8		
1045	20.7	0ml	2 minute shut down period 18.8		Unit shut itself down due to compressor overheating
1050	21.7	500ml	11.9	54 mm	
1055	21.7	500ml	11.9		
1060	20.9	500ml	12		
1065	20.9	500ml	12.2		
1070	21.7	0ml	2 minute shut down period 18.6		Unit shut itself down due to compressor

					Overheating
1075	21.7	500ml	12.4	59 mm	
1080	22.1	500ml	12.3		
1085	22.3	500ml	12.7		
1090	22.1	500ml	12.4		
1095	22.1	500ml	12.4	64 mm	
1100	22.1	0ml	5 minute shut down period 19.1		Unit shut itself down due to compressor overheating
1105	21.7	0ml	12.5		
1110	21.7	0ml	12.4		
1115	21.7	0ml	12.5		
1120	21.7	0ml	2 minute shut down period 18.6		Unit shut itself down due to compressor overheating
1125	21.7	500ml	12.5		
1130	20.9	500ml	12.7		
1135	21.7	500ml	12.6		
1140	21.7	500ml	13	69 mm	
1145	21.7	500ml	12.9		
1150	21.7	500ml	13.1		
1155	21.7	500ml	13.4		
1160	21.7	500ml	13.7	74 mm	
1165	21.7	500ml	13.7		
1170	21.7	500ml	14.1		
1175	21.7	500ml	13.9		
1180	21.7	500ml	14.3	79 mm	
1185	21.7	500ml	14.2		
1190	21.7	500ml	14.5		Photographs
1195	21.7	500ml	14.6		
1200	21.7	500ml	14.9	84 mm	
1205	21.7	500ml	14.8		
1210	21	0ml	14.8		
1215	21.7	500ml	15.2	86.5 mm	
1220	21.7	0ml	15.1		
1225	21.7	0ml	15.3		
1230	21.7	0ml	15.1		
1235	21.7	0ml	2 minute shut down period 18.8		Unit shut itself down due to compressor overheating
1240	21.7	0ml	15.1		
1245	21.7	0ml	15.1		
1250	21.7	0ml	15.1		
1255	21.7	0ml	15		
1260	21.7	0ml	15.2		
1265	21.7	0ml	2 minute shut down period 18.8		Unit shut itself down due to compressor overheating
1270	21.7	0ml	14.9		
1275	21.7	0ml	14.9		
1280	21.7	0ml	14.7		
1285	21.7	0ml	14.9		
1290	21.7	0ml	15		
1295	21.7	0ml	14.7		

1300	21.7	0ml	14.3		
1305	21.7	500ml	14.4		
1310	21.7	500ml	14.7	89 mm	
1315	21.7	500ml	15.1		
1320	21.7	500ml	15.2		
1325	22.1	500ml	15.4		
1330			1 minute shut down period 18		Unit shut itself down due to compressor overheating
1335	22.1	500ml	15.1	94 mm	
1337	22.1	0ml	2 minute shut down period 19.3		Unit shut itself down due to compressor overheating
1340	22.1	0ml	15.1		
1341	22.1	0ml	2 minute shut down period 19.5		Unit shut itself down due to compressor overheating
1345	22.1	500ml	14.9	>95 mm	
1350	22.1	0ml	Unit shut down. Requires manual restart		Unit shut itself down due to high pressure in compressor.

Toshiba Testing – Wet

Time (minutes)	Room temperature Celsius	Amount of ash added	Amount of water added at 21 degrees C	Cold air temperature degrees Celsius	~ Equivalent depth of ashfall	Notes
0	22.1	0ml	0ml	11.2	0 mm	Warmer temp than beginning of dry test, due to residual ash in unit?
5	22.1	0ml	150ml	11.2		
10	21.7	500ml	150ml	11.3		
15	21.7	500ml	150ml	11.5		
20	21.7	500ml	150ml	11.5		
25	21.7	500ml	150ml	11.7	5 mm	
30	21.7	500ml	150ml	11.7		
35	21.7	500ml	150ml	11.6		
40	21.7	500ml	150ml	11.8		
45	21.7	500ml	150ml	11.7	10 mm	
50	21.7	500ml	150ml	12		
55	21.7	500ml	150ml	12.2		Photographs
60	21.7	500ml	150ml	12.2		
135	20.7	0ml	0ml	12.5		Note break in ash addition, unit still operating
140	21.7	500ml	150ml	12.4	15 mm	
145	21.7	500ml	150ml	12.5		
150	21.7	500ml	150ml	12.7		
155	21.7	500ml	150ml	12.5		
225	22.1	0ml	0ml	13.2		Note break in ash addition, unit still operating
230	22.1	500ml	150ml	13.3	20 mm	
235	22.1	500ml	150ml	13.7		
240	22.1	500ml	150ml	13.2		
245	22.1	500ml	150ml	13.3		
250	22.1	500ml	150ml	12.9	25 mm	
255	22.1	500ml	150ml	12.9		
260	22.1	500ml	150ml	13.4		
265	22.1	500ml	150ml	13.1		
270	22.1	500ml	150ml	13.3	30 mm	
275	22.1	500ml	150ml	13.4		
280	22.1	500ml	150ml	13.6		Photographs after this reading, top removed, some ash dislodged in process

310	21.7	0ml	0ml	13.5		
						End of testing for day
315	unit started up	0ml	0ml	N/A		
375	21.7	0ml	0ml	11.8		
380	21.7	500ml	150ml	11.6		
385	21.7	500ml	150ml	11.6	35 mm	
387	21.7	0ml	0ml	17		External unit shut self down for 2 minutes 30 seconds - compressor overheating
390	21.7	500ml	150ml	12.2		
395	21.7	500ml	150ml	11.7		
400	21.7	500ml	150ml	11.9		
405	21.2	500ml	150ml	11.8	40 mm	
410	21.7	500ml	150ml	12		
415	21.7	500ml	150ml	11.7		
420	21.7	500ml	150ml	11.7		
430	21.7	500ml	150ml	11.7	45 mm	
435	21.7	500ml	150ml	12		
440	21.7	500ml	150ml	12.1		
445	21.7	500ml	150ml	12		
450	21.7	500ml	150ml	12	50 mm	
455	21.7	500ml	150ml	12		
460	21.7	500ml	150ml	12.2		
465	21.7	500ml	150ml	11.9		
470	21.7	0ml	0ml	18.5		External unit shut self down for 4 minutes 30 seconds - compressor overheating
475	21.7	500ml	150ml	12	55 mm	
480	21.1	0ml	0ml	12.1		No ash addition for next 2 hours to determine if unit can clear self
485	21.7	0ml	0ml	12.2		
490	21.7	0ml	0ml	11.9		
495	21.7	0ml	0ml	12.1		
500	21.7	0ml	0ml	12.4		
505	21.4	0ml	0ml	11.9		
510	21.1	0ml	0ml	18.2		External unit shut self down for 4 minutes 30 seconds - compressor overheating
515	21.7	0ml	0ml	12.1		
520	21.7	0ml	0ml	12		

525	21.7	0ml	0ml	12		
530	21.7	0ml	0ml	12.2		
535	21.7	0ml	0ml	12		
540	21.7	0ml	0ml	12		
545	21.7	0ml	0ml	12		
550	21.7	0ml	0ml	12.4		
555	21.7	0ml	0ml	12.1		
560	21.7	0ml	0ml	11.9		
565	21.7	0ml	0ml	18.6		External unit shut self down for 4 minutes - compressor overheating
570	21.7	0ml	0ml	12.7		
575	21.7	0ml	0ml	12.1		
580	21.7	0ml	0ml	12.3		
585	21.7	0ml	0ml	12.4		
590	21.7	0ml	0ml	12		
595	21.4	0ml	0ml	18.8		External unit shut self down for 4 minutes - compressor overheating
600	21.1	0ml	0ml	12.4		
605	21.4	500ml	150ml	12.7		
610	21.4	0ml	0ml	20		External unit shut self down for 4 minutes - compressor overheating
615	21.7	500ml	150ml	11.9		
620	21.7	500ml	150ml	12.1		
625	21.7	500ml	150ml	12	60 mm	
630	21.7	0ml	0ml	18.8		External unit shut self down for 5 minutes 30 seconds - compressor overheating
635	21.7	500ml	150ml	12.1		
640	21.7	500ml	150ml	12.1		
645	21.7	500ml	150ml	12		
650	21.7			19.1		External unit shut self down for 4 minutes 50 seconds - compressor overheating
655	21.7	500ml	150ml	12	65 mm	
660	21.7	500ml	150ml	12.5		
665	21.7	500ml	150ml	12.6		
670	21.7	0ml	0ml	19.9		External unit shut self down for 4

						minutes - compressor overheating
675	21.7	500ml	150ml	12.6		
680	21.7	0ml	0ml	12.9		
685	21.7	500ml	150ml	12.8	70 mm	
690	21.1	500ml	150ml	12.9		
695	21.7	0ml	0ml	20		External unit shut self down for 2 minutes - compressor overheating
700	21.7	500ml	150ml	12.9		
705	21.7	500ml	150ml	12.8		
710	21.7	500ml	150ml	12.9	75 mm	
715	21.7	500ml	150ml	12.9		
720	21.7	500ml	150ml	13.1		
725	21.7	500ml	150ml	13.1		
730	21.7	0ml	0ml	20.5		External unit shut self down for 2 minutes 40 seconds - compressor overheating
735	21.7	500ml	150ml	13.2	80 mm	
740	21.7	500ml	150ml	12.7		
745	21.7	500ml	150ml	12.3		
750	21.7	0ml	0ml	20.7		External unit shut self down for 5 minutes - compressor overheating
755	21.7	500ml	150ml	12.3		
760	21.7	500ml	150ml	12.6	85 mm	
765	21.7	500ml	150ml	12.3		Photographs
770	21.7	0ml	0ml	21.4		External unit shut self down for 5 minutes - compressor overheating
775	21.7	500ml	150ml	12.4		
780	21.7	500ml	150ml	12.5		
785	21.7	0ml	0ml	21.7		External unit shut self down for 5 minutes - compressor overheating
790	21.7	500ml	150ml	12.1	90 mm	
795	21.7	500ml	150ml	12.7		
800	21.7	500ml	150ml	13.1		
805	21.7	0ml	0ml	22.1		External unit shut self down for 4 minutes 30

						seconds - compressor overheating
810	21.7	500ml	150ml	12.4		
815	21.1	500ml	150ml	12.3	95 mm	
820	21.1	0ml	0ml	22.4		External unit shut self down for 3 minutes 50 seconds - compressor overheating
825	21.7	0ml	0ml	12.3		
830	21.7	0ml	0ml	12.4		
835	21.7	0ml	0ml	12.4		
840						External unit shut self down, unit manually switched off, end of ash addition.

Tohiba unit output temperatures 4 hours after the end of ashfall.	
0 m	21.9
1 m	17.1
2 m	13
3 m	12.5
4 m	12.4
5 m	12.1
6 m	12.1
7 m	12.2
8 m	12.2
9 m	12.1
10 m	12.2
11 m	12.4
12 m	12.4
13 m	12.4
14 m	12.5
15 m	12.6
16 m	12.3
17 m	12.4
18 m	12.4
19 m	12.4
20 m	15.5
21 m	19.3
22 m	22.1
23 m	22.1
24 m	22.1
25 m	19.4
26 m	14.7
27 m	12.6
28 m	12.1
29 m	12.2
30 m	12.4
31 m	12.2
32 m	12.2
33 m	12.3
34 m	12.5
35 m	12.3
36 m	12.2
37 m	12.2
38 m	12.3
39 m	16
40 m	22
41 m	22
42 m	22
43 m	22
44 m	17.6
45 m	13.3
46 m	12.4
47 m	12.2
48 m	12.2
49 m	12.3
50 m	12.4
51 m	12.5

52 m	12.6
53 m	12.5
54 m	12.5
55 m	12.5
56 m	12.3
57 m	12.4
58 m	12.4
59 m	12.4
60 m	18.6

APPENDIX 2

Airports and Volcanic Ash in New Zealand

Impacts, Mitigation and Response

A report prepared for Auckland Airport and Air New Zealand

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Introduction

Hazards posed by volcanic ash to airborne aircraft are widely recognised. Flying into ash clouds causes abrasion to all forward facing surfaces, ingestion of ash into any openings and most importantly, engines. The accumulation of ash in the turbines will then melt, possibly fusing on the high pressure nozzle guide vanes and turbine blades, eventually causing engine surge, thrust loss and possible flame out (ICAO, 2001). From 1973 through 2000, about 100 encounters of aircraft with airborne volcanic ash were documented. An average of two reported encounters per year since 1991 have occurred (a large number of aircraft-ash encounters occurred in that year due to the Pinatubo eruption), further unreported encounters are likely. (Guffanti & Miller, 2002). However ash may also cause significant physical and economic damage to grounded aircraft and airport infrastructure.

The frequency of ashfall actually landing on airports is far less than airborne encounters, however disruptions to airports due to volcanic activity are more common. These include the closure of airports and/or airspace due to the presence of airborne ash, even if the airport itself is not physically impacted. A database of all known airports that have been affected by volcanic ash between 1944 and 2006 was published as a USGS open file report by Guffanti (2007). This records volcanic activity affecting 101 airports on 171 occasions over 28 countries, and involves eruptions at 46 volcanoes (figure 4.1) (Guffanti et al., 2007). The database includes closures to airports due to ash in nearby airspace, and occasionally volcanic hazards other than ashfall (pyroclastic flows, lava flow, gas emissions and phreatic explosions).

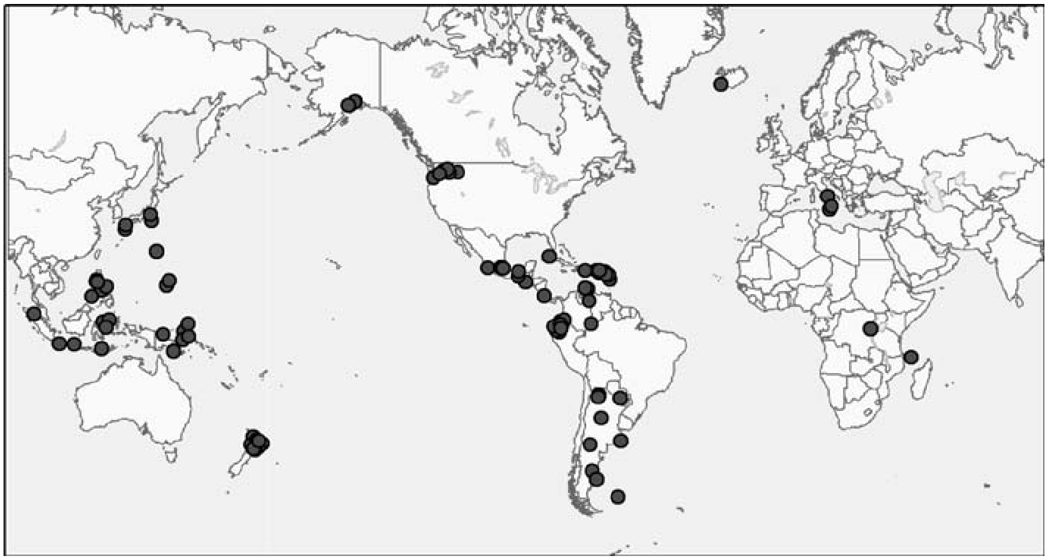

Figure 1 locations of airports impacted by volcanic activity, 1944–2006 (Guffanti et al., 2008)

An analysis of the database indicates that between 1944 and 2006 ashfall landed on an airport on at least 73 occasions, with thickness ranging from trace amounts to a maximum of 50 cm (Guffanti et al., 2007). Since 2006 there have been further incidents of this nature. For example the 2008 eruptions of Chaiten Volcano in Chile have resulted in disruptions to 5 airports in Chile, 9 in Argentina and 2 in Uruguay (Guffanti, M., pers. comm. 2009). Five of these airports are located over 100 km from Chaiten; one is over 2000 km away. These disruptions ranged from airport closures to cancelled flights.

The physical impacts of ash on airports and grounded aircraft have been addressed by several publications. Casadevall (1993), Casadevall et al., (1996), ICAO (2001) and Guffanti et al., (2008) all describe many of the ashfall hazards faced by airports and grounded aircraft. This report seeks to augment the information from those sources. Most existing knowledge on how airport authorities can deal with volcanic ash lies with the airports that have experienced ashfall. This report draws on the experience gained by two airports that have received significant ashfall in the last few years, Aeropuerto Internacional Mariscal Sucre in Quito, Ecuador, and Fontanarossa Airport in Catania, Italy. While many of the techniques employed by these two airports concur with the strategies given in previous work, their own experiences have provided useful information on best practice methodologies for responding to ashfall. Recent laboratory work conducted at the University of Canterbury also provides some insight into the potential effects of volcanic ash on aircraft surfaces.

Hazards caused by volcanic ash

Volcanic ash is hazardous for several reasons. It consists of very small fragments (<2 mm diameter) of volcanic rock and glass. Because of this small size it is difficult to prevent it getting into buildings, vehicles, and machinery. The hard nature of volcanic ash renders it extremely abrasive, whether it is from a mafic or more silicic source. As its small size makes it very penetrative, it can cause much damage by abrading moving parts on machinery. It is also respirable, creating a health hazard, potentially more so for asthmatics (Horwell & Baxter, 2006).

Ash is heavy, and it can be produced and deposited in large volumes. The weight of thick deposits of ash may exceed design loads for structures. Furthermore it may absorb up to 50% of it own volume in water, increasing its weight significantly. This can lead to building and/or roof collapse, something that has featured in many historical eruptions, e.g. Tarawera 1886 (Keam, 1988), Pinatubo 1991 (Casadevall et al., 1996), and Rabaul 1994 (Blong & McKee, 1995). Roof collapse may occur with as little as ~15 cm of ash, damage may occur with even less.
Large volumes of ash can cause additional problems in terms of blockages. The usual movement of air may be restricted as ash blocks air intakes and filters on machinery, vehicles and air handling units (e.g. air conditioners). Water movement is also restricted by blocked drains and sewers. This can lead to roofs leaking if ash clogs downpipes and spoutings. Flooding and/or sewage overflows from blocked up wastewater systems are another potential hazard caused by ashfall. Thick deposits over a few centimetres can block roads to traffic, especially on hilly areas.

Aerosols attached to freshly erupted grains of ash are potentially extremely acidic, making ash very corrosive, and putting exposed metals at risk. This affects machinery, vehicles and many rooftops. The same acidic properties can contaminate water supplies if reservoirs are above ground.

As well as the problems caused by abrasion, loading, blockages and corrosion, the slipperiness of small grains of volcanic ash constitutes a hazard in itself. This has in the past caused traffic accidents due to loss of traction (e.g. Barnard, 2004).

Background

Volcanism in New Zealand

New Zealand's geographic location on the boundary of the Pacific and Australian plates makes it a very active place geologically. The North Island hosts several active volcanoes, most of which could potentially deposit ash over any parts of the North Island, or in rare cases even the South Island (figure 1.2).

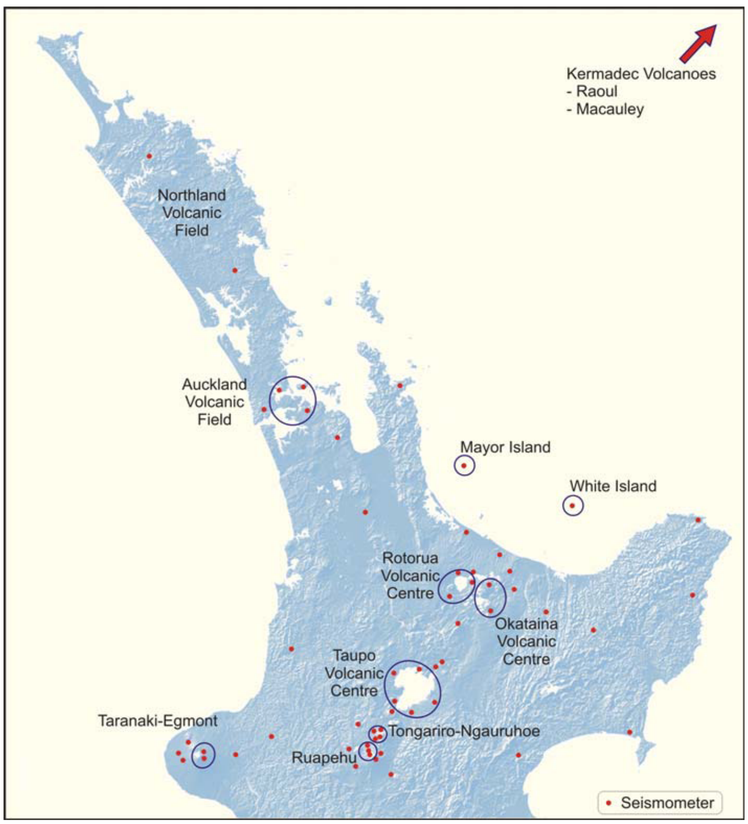

Figure 2: Seismic stations, major volcanic centres and cones of the North Island. (from Scott & Travers, 2009)

The most frequent source of volcanic ash in the New Zealand in the last 150 years is the Tongariro Volcanic Centre (Cole & Nairn, 1975; Guffanti et al., 2008) Predominant wind directions in the North Island are from west to east, therefore the cities and towns of the Eastern North Island have historically been most at risk of experiencing ashfall from this source. However the greatest risk in terms of damage from ashfall exists in New Zealand's largest city; Auckland. This is in part due to the potential economic consequences of ashfall on Auckland, but also because Auckland itself is situated on an active basaltic volcanic field (the Auckland Volcanic Field, or AVF). Moreover the active volcanic centres of the Taupo Volcanic Zone have all deposited ash on Auckland in the past (Sandiford et al., 2001). Auckland is also at risk from Taranaki Volcano; the probability of tephra-induced building damage occurring in Auckland from this volcano may be greater than from a local eruption, due to the higher probability of an eruption from Taranaki than Auckland (Magill & Blong, 2005). Local eruptions in Auckland, while statistically less frequent have the capacity to cause far more damage. The Rangitoto eruption was not only the most recent, occurring approximately 600 years ago, but the largest in this volcanic field (Magill et al., 2005). Should a similar magnitude eruption occur in the future, Auckland city would be subject to a range of volcanic hazards, such as ballistic ejecta, lava flows and base surges. A probabilistic tephra fall simulation for Auckland has calculated maximum tephra thicknesses of 150 mm for the AVF, 12 mm for andesitic centres and 830 mm for rhyolitic centres (Magill et al., 2006). Given activity to date, and the area of the AVF, the most likely scenarios would see Auckland Airport affected by ashfall rather than more proximal volcanic hazards (such as large ballistic ejecta or lava).

While it can not be accurately predicted when a local eruption from the AVF will occur, warning times in the event of an eruption may be short. A rapid onset eruption could potentially give only a few days warning (Sherburn et al., 2007). The panic likely to ensue in Auckland should a local eruption be predicted would make it very difficult to secure the necessary resources to cope with such an event. The volume of ash produced by an eruption in Auckland would depend not only on the magnitude of the eruption, but on the eruption style. Auckland volcanic field is basaltic in composition. Previous activity includes both effusive and explosive eruptions.

Strombolian, Hawaiian and phreatomagmatic eruptions have all occurred in the Auckland Volcanic Field, with cone building events outnumbering maars and tuff rings (Houghton et al., 2006). Given the geography of the greater Auckland region, the likelihood of magma encountering water near the surface is high. Ensuing phreatomagmatic eruptions may produce large amounts of ash, at least for a short time. While the basaltic nature of the Auckland volcanic field indicates a likelihood of small amounts of volcanic ash compared to a more silicic eruption, less than 1 mm of ash is needed to close airports; the 1995 and 1996 eruptions of Ruapehu illustrated this well; pre-event preparedness is essential.

Eruption Warnings

Warnings for the aviation sector about impending or current eruptions will come from GNS science and the GeoNet project, via the Wellington Volcanic Ash Advisory Centre (VAAC). Standard VAAC data is augmented by an additional service known as VAAS *(NZ Volcanic Ash Advisory System)* established by the NZ Meteorological Service and GNS Science after the 1995 and 1996 eruptions of Ruapehu (Scott & Travers, 2009). This ensures the rapid dissemination of information such as SIGMET and NOTAMs to airlines and airports.

Recommendations for Pre-eruption preparedness for Auckland Airport

Required equipment/supplies

A large part of pre-eruption preparedness consists of stocking up on supplies and equipment that will be used during and after ashfall occurs. These items include:

Maintenance equipment and spare parts: The abrasive nature of ash may cause damage or failure to exposed mechanical equipment and vehicles. Spare parts, oil filters, air filters, lubricants, and seals need to be readily available when machinery needs repair. Vehicles working in ash environments will need regular servicing. Cleaning and replacement as required of air filters is of particular importance.

Cleaning equipment: Extra cleaning supplies will be required, brooms and vacuum equipment will be in constant use. Ash will easily be carried inside buildings as people move in and out, so supplies for cleaning the inside as well as outside of buildings will be required.

Sufficient tarpaulins and duct tape to cover the windshields, nose cones, pitot tubes, engine intakes and wheel assemblies of any aircraft that may be grounded during the course of the eruption are needed. While it is a better option to remove aircraft pre-eruption, this may not be possible if warning times are insufficient to do so. The small expense entailed in stockpiling such items will protect grounded aircraft from the worst of the damage that may occur with small amounts of ashfall. Tarpaulins and duct tape may also be used to cover mechanical or electronic equipment that may not otherwise be adequately protected. Where possible, if time permits, essential air conditioners should be sheltered from direct ashfall. This will allow them to continue to function at near usual levels of performance if ash ingress is inhibited.

Dust or filtration masks for workers involved with ash clean up, or simply working in ash affected environments need to be acquired. Recommended masks are described by the International Volcanic Health Hazard Network, available at http://www.dur.ac.uk/claire.horwell/ivhhn/guidelines/masks/masks.html. Sufficient masks to be provided for all involved staff for at least one week should be sourced if warning of a distal andesitic eruption is given. In the event of an impending eruption in Auckland or in the unlikely event of a large scale rhyolitic eruption (e.g. Taupo Volcano) this amount of masks should be significantly increased. Such items are likely to be in short supply when an eruption has been predicted. Enough goggles for workers cleaning up ash should also be available, ash caught in the eyes is very painful, and may scratch the cornea.

Harnesses and ropes are already employed by Auckland Airport for use when workers are performing maintenance work on rooftops. These will be especially important when cleaning slippery ash covered rooftops. Adequate numbers of harnesses need to be available to ensure terminal and hangar roofs can be quickly cleaned before too much ash enters downpipes, damages or even collapses roofs.

Access to sufficient road sweeper/vacuum trucks needs to be established pre-event, if the airport itself does not possess adequate machinery. The quantity of trucks available will determine the speed at which the airport is made operational again. Past experience of ashfall at Fontanarossa airport, Italy suggests that in order to remove 1 mm of ash from runways, one standard road vacuum/sweeper truck can clean 5000 m^2 in one hour. This may take slightly longer at first if operators are unfamiliar with this type of task.

Ash deposited on runways needs to be removed, which in turn entails it being deposited somewhere. The location of a dump or temporary storage site should be established pre-event. Volumetrically a large amount of ash will be removed from the runways and taxiways, even a 1 mm covering will result in over 300 m^3 of ash on the >300000 m^2 of runways at Auckland Airport. Ash on green areas may be ploughed into the soil for stabilisation. Access to such equipment as rollers and pulvimixers may need to be arranged pre-event. Time required to perform these tasks is again estimated from that taken by Fontanarossa. Airport operators SAC (Societa Aeroporto Catania) report that 1000 m^2 takes approximately one hour for one pulvimixer/roller.

Trucks to take away and dump ash will also need to be sourced pre-eruption, as may additional water tankers to dampen ash before removal, to prevent remobilisation into the air.

Front-end loaders will be required to load ash onto trucks, especially from piles swept off roofs etc; access to this type of machinery should be arranged pre-event.

Should a large scale local event be predicted (one that may result in large amounts of volcanic ash), additional machinery may be required. Ash will need to be bladed to the side of the runways using snow-plough or grader type equipment, before being loaded onto dump trucks using front end loaders. The more machinery available the faster clean up will occur.

Large amounts of water will be required by the clean-up operation, however it is understood that Auckland Airport is self sufficient in this regard. Back-up generators and fuel may also be necessary as power-cuts may be caused by ashfall.

Other planning issues

Plans and rosters need to be established for 24-hour maintenance operations. Procedures detailing the roles and responsibilities of all teams during and after ashfall are required prior to an event, to enable efficient and rapid response. Communications may be adversely affected by volcanic ash, as overloading of phones is common in emergencies, and power loss exceeding a few hours can result in telecommunications exchange failure. Staff may therefore be difficult to reach. It should be noted that eruptions can continue for weeks or months. In an eruption in the Auckland Volcanic Field this may result in ashfall affecting the airport on numerous occasions.

Deposits of ash over ~15 centimetres may render roads impassable to two-wheel-drive vehicles, roads are likely to be closed to non essential traffic before this. This will have implications for the availability of staff trying to get to and from work, and needs to be considered in planning rosters etc. Furthermore in the event of a local eruption some staff may be evacuated from their homes, and may therefore be unavailable for work.

A list of facilities that are essential to the operation of the airport needs to be complied, so that non essential machinery and facilities may be closed down for the duration of the ashfall.

Where possible, it is preferable to move aircraft pre-eruption rather than trying to cover them up or park in hangars. If an eruption becomes prolonged, or the airport is closed for several days, the aircraft may be trapped on the ground. This happened to the Ecuadorean airline TAME, during the 2002 Reventador eruption, when 7 of the airlines fleet of 11 aircraft were trapped on the ground for the duration of the clean-up (figure 2). This caused major financial losses for the airline (Leonard et al., 2005).

Communication with GNS Science and the Meteorological service will be critical in deciding when an ash cloud is likely to impact the airport or air space.

Figure 2: Boeing 727 with makeshift covers during ashfall, Quito, November 2002, photo courtesy Mariscal Sucre Airport.

Eruption Response

Health and safety

Before any activity is undertaken in volcanic ash environments, the safety of employees must be taken into account. The most useful safety equipment consists of goggles and a dust/filtration mask. These are essential for workers involved with ash clean up, or simply working in ash affected environments. Workers with asthma or other respiratory conditions should not work in these conditions.

The slipperiness of ash covered surfaces also creates hazards, this is especially prevalent on rooftops, where workers must be harnessed at all times. Speed restrictions need to be applied for any vehicles being driven in the ash environment, as not only will they stir up ash, but the slipperiness of ash covered surfaces and reduced visibility (during ashfall) make driving conditions dangerous.

Grounded aircraft

As soon as possible after the start of an eruption, or after an eruption warning, aircraft not able to be flown out of the airport need to either be parked in hangars or protected by means of tarpaulins/plastic sheeting. Any vulnerable parts should have these types of covers placed over them, using adhesive tape to secure. Parts commonly identified as vulnerable include windscreens and nosecones, engine intakes and wheel assemblies. Pitot tubes should also be covered. All flaps, spoilers etc should be fully closed. If possible any further seams, ports or vents should be sealed with duct tape and plastic sheeting. The amount of sealing and covering will depend on available time and labour.

Should a significant ashfall (over 5cm or so) be expected, any aircraft with engines at the tail, or large surface areas (i.e. horizontal stabilizers) at the rear of the aeroplane which may accumulate large amounts of ash should be anchored to the ground at the front. This is to prevent the weight of the ash unbalancing the aircraft, rotating it back onto it's tail and damaging the underside of the aeroplane. This happened to a DC-10 and C130 at Cubi Point Naval Air Station on June 16 1991, following the Pinatubo eruption, and several B-25 bombers at Pompeii during the 1944 eruption of Vesuvius.

Due to the potentially corrosive nature of volcanic ash, aircraft need to be quickly cleaned after ashfall. Impacts to metal surfaces depend not just on the pH and the duration that ash is left on the aircraft, but on the presence of rainfall during or after ashfall. Light rain during or after ashfall could result in significant damage to ash covered aircraft, but heavy rain is likely to clean aircraft of ash, and is thus less of a problem in terms of corrosion. Recent testing has indicated dry ash has no effect on any kind of aircraft surface, but wet ash can result in leachates corroding and oxidising both clad and unclad surfaces. Tests of unclad 7075-T6 and 2024-T3 alloys with an ash leachate of pH 2.5 resulted in surface pits of 10-30 µm after 24 hours, clad surfaces experienced deeper pitting of up to 50 µm (figure 3) (Barnard, 2009).

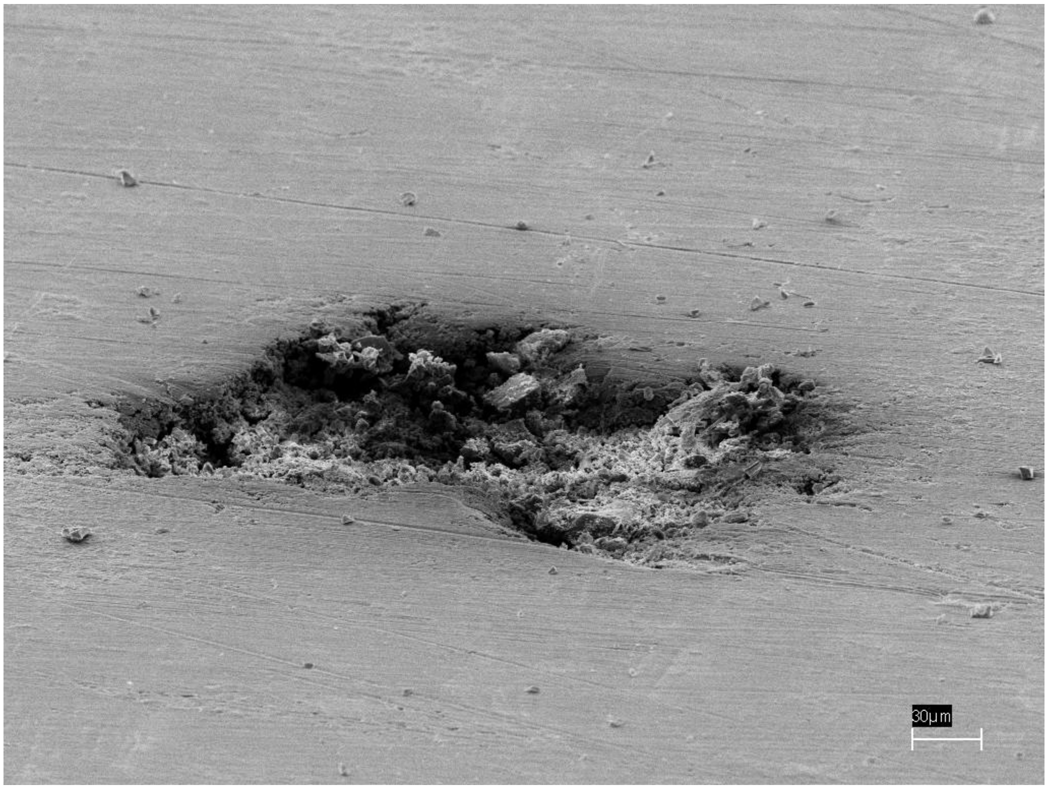

Figure 3: SEM micrograph of clad 2024-T3 aluminium after being exposed to a leachate of pH 2.5 for 24 hours

Wet ash from phreatic or phreatomagmatic eruptions will have the capacity to begin to cause corrosion immediately upon landing on the aircraft. As it is unlikely that leachate pH will be known immediately after ashfall, it will be necessary to treat any ash as being highly acidic, removing it from aircraft as soon as possible to prevent corrosion.

The amount of surface oxidation and pitting corrosion experienced in these tests would not in itself prevent aircraft flying. Oxidation of aluminium and alloy surfaces is common on aircraft; repairing oxidised surfaces is dealt with as part of routine aircraft maintenance and does not require immediate attention. Pitting is more serious, as once pits form they tend to continue to slowly grow over time. In the short term the mechanical performance of clad alloy is unlikely to be compromised by the level of pitting seen in these tests, as it is the clad surface that is corroded rather than the structural alloy. Pitting directly in alloy is more problematic, in that even aircraft skins are structural; pits can eventually lead to fatigue failure if they are located in a critical load path (Banis et al., 1999). The 10-30 μm deep pits experienced by the unclad 2024 and 7075 alloys amounted to between 1 and 3% of the 1 mm alloy thickness. This level of pitting is not sufficient to compromise the structural integrity of the alloy, but the corrosion does however need to be quickly removed and the surface repaired. Depending on the extent of corrosion this could result in the aircraft being out of service for days to weeks. Even without this damage occurring, any aircraft subjected to ashfall will require extensive inspection to ensure all ash is removed and the plane is safe to fly.

Airport infrastructure

Buildings

One of the most severe problems associated with volcanic ash is loading. Roofs will accumulate ash, enough ash can lead to collapse. (This may be in the region of 10cm or more for large span roofs). As the amount of ash likely to be produced by an eruption is not easy to predict, roofs should be cleaned frequently during the course of an eruption to prevent ash accumulating. Prior to collapse damage may be sustained such as the bending of roofing iron, resulting in the ingress of ash (and any rainfall) into buildings.

Regular cleaning is also important for roofs that drain into downpipes within buildings. Blockages of ash are likely, and may result in flooding of the building during rainfall. Minimising ash ingress into these downpipes is only realistically possible by cleaning ash off roof surfaces regularly.

Buildings that are not essential for the daily running of the airport or not in use while the airport is not fully operational should be kept closed. Any movement within buildings will mobilise ash that has managed to find its way inside. Buildings that are used should employ as few entries/exits as possible, to keep down the entrainment of ash from the outside.

Electronic equipment inside buildings should be covered as fine ash manages to penetrate even closed buildings to a certain extent, especially in windy conditions. Computers have proved to be surprisingly resilient to dry volcanic ash during laboratory tests. However should this ash become damp it becomes conductive, which will quickly cause computers and other electronic equipment to short-circuit and fail (Gordon et al., 2005).

The use of air-conditioning systems need not be avoided during ashfall. Most units will cope with light ashfall. Tests indicate ashfall up to a thickness of ~30 mm will not cause air conditioner failure, and only slightly decrease performance. Regular maintenance during ashfall is advised, as after ~30 mm of ash most split systems condensers will begin to partially block, eventually causing compressor damage, resulting in unit shutdowns. Through wall or ‘window rattler’ type units usually have a faster fan than split system types. This helps them self clean; these therefore tend to be more robust in ashfall. Care must be taken when cleaning ash from condensers as the thin aluminium fins easily bend, low pressure water can be used, as water blasting is too powerful and will damage condensers. Fresh air systems that pump outside air into the inside of buildings should not be used at all while ash is entrained in the atmosphere, as large amounts of ash will be sucked into building interiors.

Paved areas

Stormwater drains are easily blocked by large volumes of volcanic ash being washed into them. This should be avoided where possible. Sand (or ash if it has already fallen) bags may be placed around drains to help prevent this.

Ash is easily remobilised when dry. Wind picks up dry ash and blows it around, traffic and human activity will exacerbate this by stirring up ash. Any vehicles driving in ash should proceed slowly, not only because of the nuisance caused by re-entraining ash into suspension, but for safety reasons. Surfaces are slippery in both wet and dry conditions, and visibility is low when thick ash is falling. Headlights should be on. Any road/runway markings will also be invisible as the ash covers them, even at 0.5 mm thicknesses. Access airside needs to be strictly controlled to ensure the re-mobilisation of ash is kept to a minimum. Dampening the ash (with water tankers) helps to keep it from being stirred up quite so much. Soaking (as opposed to dampening) ash is not a good option, as this can cause ash to harden and cake, making it much more difficult to remove. The exact amount of water needed to dampen ash enough to stabilise it without caking it will vary depending on the type of ash, and can really only be achieved by a process of trial and error. Another option used in the past to stabilise ash includes damp sawdust, used in Spokane following the Mt St Helens eruption.

Machinery

Any machinery not in use needs to be covered with tarpaulins or put away. This will help reduce corrosion and abrasion. Any exposed moving parts will suffer. Preventative maintenance is essential, for example should any vehicles operate with a torn CV boot, failure of the CV joint is likely to be rapid (i.e. within a few kilometres). Brake assemblies will need to be cleaned every 100 to 200 km in heavy ash conditions, as will oil filters. Air filters will possibly need to be cleaned, (compressed air, blowing from inside to outside) or at least inspected daily. After the eruption has ceased and the ash has been cleaned up, vehicles and other machinery should undergo a full service, replacing all fluids, filters etc.

Clean-up Operations

Aircraft

Cleaning ash off aircraft surfaces needs to be approached with care to avoid abrasion. Recent testing of aircraft surfaces with andesitic ash from Rabaul using both low pressure water and brushes resulted in negligible abrasion occurring, however different ash types may give different results. The ash used in testing was a fine grained dacite, its high silica content and angular grain shape made this a very abrasive ash. Volcanic ash could potentially be more abrasive than this, causing damage to surfaces. This could occur with a more silicic rhyolitic ash, or even a glassy ash with sharp angular grains. Extreme care should therefore be taken when removing ash from aircraft skins. Abrasion to windshields and windows was not tested, as experience after the Pinatubo eruption suggests these can easily be scratched if rubbed when removing ash (Casadevall, 1992). Ideally windshields should be covered in the event of an aircraft being parked outside during an ashfall

Ash should be gently hosed and brushed with soft brushes if it is wet or has been wetted on the aircraft. Dry ash can also be vacuumed if time and resources permit. The use of fire engines to wash clean aircraft in Quito was employed in 2002. This was apparently successful, with no damage reported to aircraft. A timeframe of 10-15 minutes for a basic hosing clean of a Boeing 737 using a single appliance was given. Care must be urged when using this technique, to avoid washing ash into any seams, ports or vents. With high pressure water there is a risk of abrasion as ash particles move against aircraft surfaces.

After cleaning the bulk of the aircraft, protective coverings on more vulnerable parts may be removed and these areas carefully cleaned as required. Windscreens and wipers impacted by ash need to be carefully cleaned by hand, without rubbing (dab instead) as ash caught under windshield wipers will abrade the windscreen when the wipers are used.

Thorough inspection of the aircraft is required afterwards to ensure that intakes/vents, and any moving parts are not contaminated with ash.

Airport Infrastructure

Buildings

Clean from the top down. Start with rooftops, otherwise ash will be remobilised from these areas onto lower surfaces. Cleaning below buildings then sweeping ash off the roof will create extra work. Other reasons for cleaning roof tops first include the prevention of loading damage should further ashfall occur. Cleaning rooftops can be a hazardous business. Care must be taken by workers, due to the slippery nature of both wet and dry volcanic ash, harnesses are therefore essential. An exclusion zone should be marked on areas underneath the building where ash is likely to be falling off. Should a large amount (>5 cm) of ash be present on the roof, extra care is needed as the additional weight of workers will stress already overloaded roof tops (especially large span hangar/terminal type roofs).

To prevent excess ash being washed into gutterings and downpipes, brooms and shovels should be used on rooftops rather than hoses and water. However should downpipes become blocked with ash they can be cleaned using high pressure water. This method has been employed successfully by Fontanarossa airport. Sweeping ash onto lower roofs must also be avoided, the impact of a large volume of falling ash may be sufficient to cause lower roofs to collapse. The accumulation of ash in overhanging gutterings may cause them to collapse. This may be difficult to avoid if trying to rapidly clean roofs by sweeping ash off them onto the ground, in order to restore operations as quickly as possible.

Building Interiors

The following suggestions for cleaning building interiors are taken from the USGS website, (http://volcanoes.usgs.gov/ash/build/index.html#remove). This website has been contributed to by several organisations, including GNS Science, and the University of Canterbury.

- *Cleaning by blowing with compressed air or dry sweeping should be minimized.*
- *A dustless method of cleaning such as washing with water and an effective detergent/wetting agent is recommended. Damp rag techniques should be used whenever possible to remove the substance from small surface areas or flooring. On those areas where damp rag techniques cannot be implemented (for example, carpets) vacuum cleaning methods should be applied.*
- *After vacuuming, carpets and upholstery may be cleaned with a detergent shampoo. Avoid excess rubbing action because the sharp ash particles may cut textile fibres.*
- *Glass, porcelain enamel and acrylic surfaces may be scratched if wiped too vigorously. Use a detergent soaked cloth or sponge and dab rather than wipe.*
- *High-shine wood finishes will be dulled by the fine grit. Vacuum surfaces and then blot with a cloth treated to pick up ash. A tack cloth used by furniture refinishers should work well.*
- *Floor sweepers with side brushes should not be used to clear aisles and floors because they may re-entrain dust particles into the air.*
- *Ash-coated fabrics should be rinsed under running water and then washed carefully.*
- *For several months after an ash fall, filters may need replacing frequently. Air conditioner and furnace filters need careful attention. Clean refrigerator air intakes. Clean any surface that may blow air and re-circulate the ash. Stove fans and vents should be cleaned thoroughly.*
- *Each employee should be responsible for clean-up of his/her own work area to minimize exposure potential during a work shift. This should be accomplished at the beginning of each shift. Damp rag or vacuum techniques should be used during this operation.*

Electronic equipment should be cleaned using vacuum cleaners.

Paved surfaces/Runways

To stabilise ash and prevent it from being remobilised, ash may need to be dampened with water trucks. This will depend on ash grainsize. For deposits over ~5 mm thick different techniques can be applied; thicker deposits need to be bladed rather than swept or vacuumed away. This will remove ash much more quickly. Piles of ash pushed to the sides of the cleaned area may then be loaded onto trucks using front end loaders. Care needs to be taken not to push ash into stormwater drains.

For thinner deposits of ash, sweeper and vacuum equipped trucks are recommended. Again ash may be slightly dampened, but not wetted. The operators of Catania's Fontanarossa airport found the best way for them to operate their trucks is lengthways along the runway, starting from the centre, moving to the outside. The timeframe given by them to clean up residual ash (~1 mm thick deposits) equates to 5000 m^2 per hour for a single truck. After sweeper/vacuum trucks had passed by water tankers were driven across the runway, cleaning residual ash from surfaces. These techniques are based on their experiences with ash from Mt. Etna in 2000, 2001 and 2002.

In the absence of available machinery, or in areas not easily accessed by trucks or street sweepers, manual labour may need to be employed. Sweeping up ash with brooms and shovels takes time, but is possible. The clean-up of runways at Quito's Mariscal Sucre Airport after the 2002 Reventador eruption was entirely performed by labourers in this way. Approximately 4 mm of ash had been deposited over Quito. It was found that time taken to sweep up, bag and remove ash equalled only about 5.5 m^2 an hour. While obviously slower than a truck, this timeframe was for a thicker amount of ash than the 1 mm or so of ash removed by truck at Fontanarossa, as described above. Workers sweeping up ash in Quito were mostly from poor communities, and were being paid a small amount per hour. It is probable that faster rates of manual clean up could be performed by workers in Auckland. Even so these rates do reflect the laboriousness of the task, and the fact that it will take a long time to complete.

Cleaning methods used in other eruptions, both successful and unsuccessful are summarised in table 1. These may be useful in situations where suggested methodologies are not working effectively.

Airport	Eruption	Amount of ash	Distance from source /grainsize	Method used to clean	Other clean-up methods tried (unsuccessfully)
Anchorage International Alaska, USA	Mt Spurr August 1992	3-6 mm Drifts to 12 mm	125km, fine	Complete saturation, flotation of finest components. Graders + brooms moved saturated ash as far as possible. Bermed ash loaded into trucks. Residual ash was removed by flushing the area with water	Dry sweeping caused too much remobilization, method abandoned. Dampening ash made a paste that was hard to move
Merrill Field Airport, USA	Mt Spurr August 1992	6-12 mm	125km, fine	Ash wetted and cleaned using a vacuum sweeper.	
Grant county, USA	St Helens may 18 1980	75-100 mm	200 km, very fine	A moderate amount of water made it like balls of clay – easier to deal with. Spray with water, windrow with grader, scoop with loader to dump truck.	Saturation with water resulted in powder-like ash behaving like soup, difficult to manage
Cubi Point NAS (plus Clark Air Force Base PHILIPPINES	June 15-16 1991 Pinatubo	150-200 mm	40km (Cubi point) 25km (Clark) sand sized	Wet ash ploughed into furrows using road graders, then loaded in to dump trucks, final sweeping with trucks. Nb Heavy rains	
Manila Ninoy Aquina International Airport (NAIA) PHILIPPINES	June 15-16 1991 Pinatubo	0.5 to 1 cm ash – fine sand to 'Powder" sized ash	~100km Fine sand to powder-size	Manual sweeping into furrows, stabilised with emulsified asphalt (to bind loose ash)	Initially furrows of ash were collected into sacks. After filling 30,000 they stopped and stabilised furrows in place with emulsified asphalt.

Table 1 major ash impacts on runways, 1980 – 1992, summarized from Casadevall (1993)

To speed up the resumption of normal services aircraft may be towed from areas still contaminated with ash to cleaned runways. The APU or engines must not be started until the clean runway area is reached.

Stormwater drains

Drains blocked with ash will cause surface flooding during subsequent rainfall. While some ash may be removed with manual labour (shovels), high pressure water may be required to clean harder to reach areas.

Green areas

Thick deposits of ash on green areas may be removed in the same way as on runways, using a blade or snowplough to push ash into piles, before being loaded onto trucks with a front-end loader. For the residual ash left, ploughing and rolling techniques can be utilised to bind the ash with the soil. Fontanarossa Airport uses a pulvimixer to do this, taking 1 hour for a pulvimixer to cover about $1000m^2$. Areas immediately adjacent to the runway are addressed first, as ash further from the runways may be sufficiently stabilised by water in the short term to begin aircraft operations again. Operations will be significantly slowed down if obstacles (such as runway lights) are found in these areas. Other possible methodologies include the use of emulsified asphalt to stabilise ash on grassed areas.

Runway inspection

A thorough runway inspection should be carried out after clean up operations, prior to the resumption of aircraft operations. This is to check for any debris or ash left on the runway, and the surface of the pavement itself. Damage may occur during clean up operations, especially when snowploughs/blades and front end loaders have been used.

Radar and optical systems

Advice on actions to take regarding radar and optical systems is from the ICAO Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds, appendix B (in italics).

Most radar equipment in the heaviest ash-fall areas has to be shut down for the duration of severe ash contamination. Thus, few problems are likely aside from clean-up and control of residual ash. The simplest mitigation tactic is to cease operations. Clean-up techniques include:

- *Repair and clean high-voltage circuits*
- *Wash antenna rotor bearings, re-lubricate, and cover exposed bearings*
- *Ash on optical components should be blown away or washed with copious amounts of water. Do not wipe or brush as this will abrade the optics*
- *Turn off non-essential radar equipment to reduce cooling load and power requirements*
- *Transfer radar coverage to other facilities, combine sectors*
- *Remove and replace camera bearings and clean gear drives*

Machinery/Vehicles

Vehicles and other machinery should undergo a full service, replacing all fluids, filters etc. Attention should be given to all moving parts, e.g. hydraulics. Brake assemblies will need to be cleaned every 100 to 200 km when being used in heavy ash conditions, as will oil filters. Air filters will possibly need to be cleaned, (compressed air, blowing from inside to outside) or at least inspected every day. After the eruption has ceased and the ash has been cleaned up, vehicles and other machinery should undergo a full service, replacing all fluids, filters etc. Glass and painted metal surfaces should not be wiped as this will cause abrasion. Compressed air or water can be used; any use of cloths should be with a dabbing rather than a rubbing motion.

Conclusion

Provided aircraft are adequately protected, and roofs are cleaned before tephra loading becomes an issue, physical damage resulting from ashfall can be minimised. However impacts to airports and grounded aircraft are not only physical. Financial losses resulting from the costs of airport closure are likely to exceed those incurred from damage and cleanup. Pre planning for ashfall is essential to minimise airport closure time, facilitating a rapid return to business as usual. A reactive approach to ashfall will result in more damage and a longer recovery time, as access to required cleaning equipment (including runway cleaning machinery) may not be possible, contacting staff may be difficult, and aircraft may be stranded and unnecessarily exposed to ashfall. Even seemingly simple omissions like a shortage of personal protective equipment such as dust masks may hinder clean up procedures, ultimately costing more in airport closure time. The mitigation strategies listed in this report will aid the process of effectively managing the risk posed by volcanic ashfall.

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